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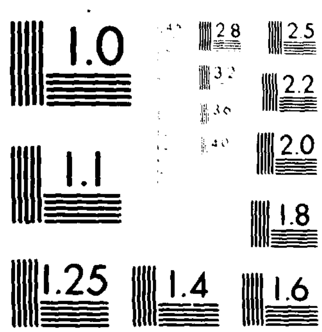

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1. INTRODUCTION AND SUMMARY

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This report documents the results of the Packet Radio Deployment Study performed by Network Analysis Corporation (NAC) for the Communications Research and Development Command (CORADCOM) at Fort Monmouth. The objective of the study is to assess the potential of the Packet Radio technology for satisfying communications requirements in the military environment. The focus of the study has been on quantifying PR network performance under the expected military traffic loads.

NAC's activities have consisted of the following three tasks:

- Task 1: Enhancements of ~~NAC's~~ the Packet Radio Simulation Program (PRSIM);

- Task 2: Implementation of a Military Scenario Model; and

- Task 3: Design, Routing and Performance Analysis of Packet Radio Networks for the Military Scenarios.

In Task 1, NAC modified PRSIM to more accurately model the capabilities of the Defense Advanced Research Projects Agency's (DARPA) Test Bed PR Network. The modifications of the NAC model included:

- Integral terminal relay capability

- Point-to-point routing

- Enhanced terminal queue management (to handle multiple TCP connections through a single origination or destination PRU)

- Local repeater on packet transmission/reception

- Enhanced statistics gathering capability

- Mobile terminal capability.

Task 2 involved the development of a computerized data base and software modules for Scenario Generation. To assist NAC in the development of these modules, MITRE (tasked by CORADCOM) prepared a detailed description of a military scenario[1]. This description was based on the deployment of packet radio units in the Fulda Gap area of Germany as part of the U.S. Army's Scores II-A scenario. The activities in this task consisted of:

- Computerizing the terminal location, traffic volume, and mobility tracks supplied by MITRE
- Developing software to transform this information into a form suitable for PRSIM
- Modifying PRSIM to accept this information.

The detailed procedures for performing this task are described in Section 2 below.

In addition, the Longley Rice propagation model [6] was implemented and PRSIM was modified to access this model to determine network connectivity. Subsequently, PRSIM was modified to accept line of sight information to determine network connectivity.

Task 3 involved detailed analysis of the PR networks using both analytic models and simulation. The issues addressed consisted of throughput-delay, survivability, routing, and repeater location.

In this task, NAC first performed a detailed analysis of network connectivity using the Longley-Rice model. The results of these studies are described in Appendix A. Because of the uncertainty of this model, it was decided to employ a LOS criteria to determine network connectivity. Using the LOS criteria to determine network connectivity, NAC performed extensive simulation to evaluate performance of a Command and Control Network under a wide range of parameters. The range of these experiments are described in Section 3 and the corresponding results in Section 4. The major conclusions are:

- C^2 traffic load can be handled by PR nets over a wide range of operating conditions.

- Mean round trip (end-to-end) message delays of less than 2 seconds in the worst case were measured. This included the increase in traffic of 100% over the estimated volume and the reduction of PRU buffers from a nominal value of 6 to 3.

- These conclusions hold for both host and direct (terminal-to-terminal) routing although the performance of point-to-point routing is superior.

- The introduction of two dedicated repeaters in the forward area near the brigades decreases the number of hops required on certain routes with host routing; hence, message and packet delays are also decreased.

- The retrograde from the initial deployment to Defense Bravo reduces network connectivity, but delay requirements are still satisfied.

- Buffer size was identified as a sensitive parameter.

In addition to the simulation performance models, NAC also developed analytic models for network throughput and survivability, these models are described in Sections 5 and 6. In the throughput models, the performance of tandem networks was first addressed. The objective was to estimate the throughput level such a network could support; tandem networks were analyzed because initial connectivity studies indicated that PR networks would be sparsely conneted. These results were subsequently applied to a general topology to obtain a lower bound on the throughput level a network could support. The resulting bound reinforced the simulation results, indicating that the network could very likely support the offered load in the Command and Control network.

For the survivability problem, tandem networks were again first addressed because the initial Longley-Rice models indicated that the network connectivity would be sparse. Three models were developed to estimate the number of repeaters required to guarantee a specified survivability level. However, with the LOS connectivity criteria, the PR networks were much more densely connected, and the survivability problem was much less complex. In this case, for the C^2 network certain Maneuver Battalions were only connected to the remainder of the network by a single repeater. However, with the introduction of two repeaters (as selected by MITRE), all Maneuver Battalions were 3-connected, which guaranteeed an adequate survivability level.

A heuristic algorithm, described in Section 7, was developed to assign routes to the needlines. The procedure is static in that routes are assigned a priori, independent of network conditions. This procedure was developed to select shortest path routes with minimal congestion, and was used in the simulations with connectivity determined by the Longley-Rice criteria.

The configuration issued addressed focused on the location of repeaters. With the topology defined by the LOS criteria, the problem was trivial, good repeater locations could be "eye balled." However, with other criteria, the configuration problem is more interesting. A procedure for selecting repeater locations is described in Section 8.

Also, as part of this study, an evaluation of the Mobile Subscriber Entry system was performed. The results of this study were presented originally to DARPA and CORADCOM in November 1978. The slides presented at that time are included in Appendix B.

2. MILITARY SCENARIO MODEL

2.1 Overview

In this section the military scenario model and the methodology for carrying out its analysis are described. In order to perform the design and analysis of the packet radio networks proposed for deployment in the military scenarios, the following software modules are required:

- Data base module
- Scenario generator module
- Packet radio simulator module
- Communications link module
- Connectivity module
- Configuration and routing module.

The interaction of these modules is schematically depicted in Figure 2.1. A solid line from module A to module B (direction denoted by an arrow) indicates that module A accesses module B as module A runs; a dashed line from module B to module A indicates that module B generates an input file for module A. The functions of the individual modules are summarized below.

A. Data Base Module

The Data Base module will consist of location, traffic, and mobility files defining the military scenarios. The information included in these files is derived from the military scenarios defined by MITRE [1] with only minimal algebraic transformations performed for convenience. This module, which is described in detail in Section 2.2, was developed as part of Task 2.

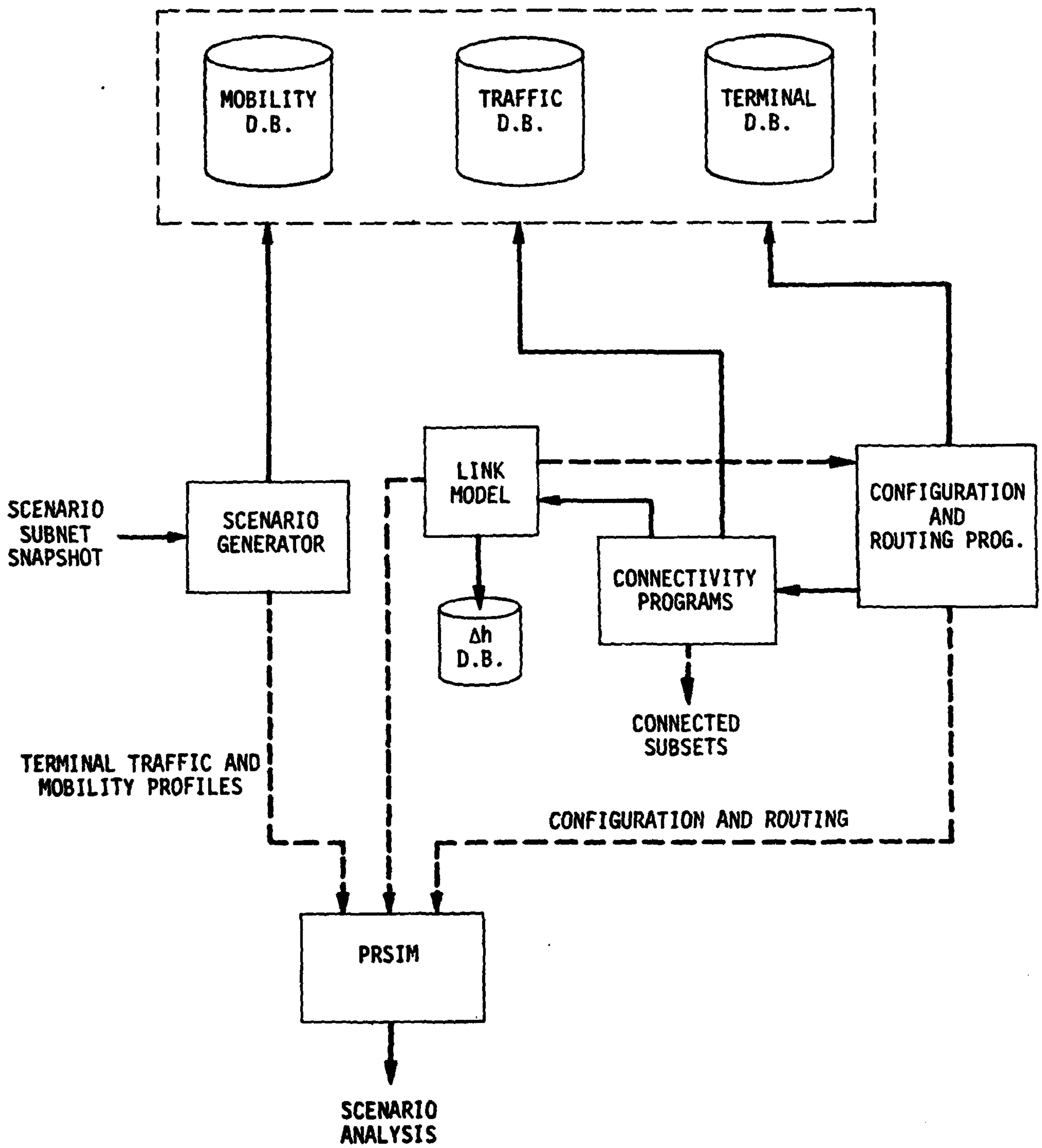

FIGURE 2.1: MODULE INTERRELATIONSHIP

B. Scenario Generator Module

As depicted in Figure 2.1, the Scenario Generator Module accesses the location, traffic, and mobility files in the Data Base Module and then generates input files for the packet radio simulation module. The major parameters describing a scenario are:

- Subnetwork
- Snapshot
- Time duration.

In this study, only the Command and Control subnetwork was simulated although data bases were created for Field Artillery and Air Defense applications.

As combat conditions dictate, the PR units will have to be reorganized; hence, three snapshots were defined. A snapshot defines a particular deployment of the packet radio units for the specified subnetworks; the following deployments have been defined:

- Initial D day H hour deployment
- D day H+6 hours deployment along Defense Line (DL) ALPHA
- D day H+24 hours deployment along Defense Line (DL) BRAVO.

Only the initial deployment and DL Bravo snapshots were simulated.

The Scenario Generator has the capability of generating a traffic profile for traffic routed directly terminal-to-terminal or via a message-switching host. The time duration input parameter defines the length of time covered by the scenario. The needlines have been defined on a terminal basis for each subnetwork, independent of deployment. However, adjustments to the traffic flows are made to account for terminals that are lost, captured, or destroyed between subsequent scenarios.

After a terminal has been lost, destroyed, or captured in a particular deployment, the terminal is not included in subsequent deployments (and hence, obviously will not transmit any messages). However, in the subsequent deployments it is assumed that all terminals

that transmit are aware of all potential destination terminals that have been lost, captured, or destroyed; hence, terminals do not attempt to transmit to these terminals that have been lost due to attrition.

The output of the Scenario Generator consists of the following files to be used as input for the packet radio simulation module:

- A PR locations file specifying coordinates of each terminal PR in the subnetwork being considered.

- A traffic file specifying the times of transmissions, the transmitting PR, receiving PR, and other message parameters.

- Mobile PR locations as a function of time.

C. Packet Radio Simulation Module

The Packet Radio Simulation Module is based on NAC's existing packet radio simulator PRSIM. This program was extensively modified to reflect more accurately the PR test bed protocols (as part of Task 1) and to accept data for the military scenario (as part of Task 2). This module performs the detailed performance evaluation of the packet radio deployments and requires the following input:

- Terminal location, traffic, and mobility files from the Scenario Generator.

- Repeater location and routing procedures from the Configuration and Routing Module.

- PR operational parameters supplied by the user; these parameters are discussed in Section 2.5.2.

In addition, PRSIM accesses a Link Model file in order to determine the network connectivity.

Given the above information as network configuration, traffic, and protocols, PRSIM simulates the network operation to measure accurately such quantities as:

- Average one-way packet and message delay (excluding ETE ACK)
- Average round-trip packet and message delay (including ETE ACK)
- Buffer utilization
- Throughput.

These statistics are more precisely defined in Section 3.2.5.2.

D. Communications Link Module

The Communications Link module is used to determine whether the two PR units can communicate directly without the aid of any intermediate repeating devices. If they can, a link between the PR units exists.

Two criteria were employed to define the links in the scenario networks, namely, a line of sight criteria and an attenuation loss criteria, based on the Longley Rice model. MITRE Corporation supplied the terrain profiles for the LOS criteria. In this case, it was assumed that devices could communicate if an only if they were in LOS of each other. In all cases, the free space attenuation loss was less than 150 dB, the threshold attenuation specified by CORADCOM.

Alternatively, using the Longley Rice program supplied by CORADCOM as a subroutine, the Link module can compute the transmission loss between any two PR units. Then, if the transmission loss does not exceed a specified threshold (which is a function of data rate), it is assumed a link exists between the two units. The transmission loss computed by the Longley Rice for two PRU's, A and B, is independent of which of the two PRU's is transmitting or receiving. Thus, if A can hear B, then B can hear A, and vice versa. In a graph theoretic sense, the PR network is said to be undirected. The analogous assumption was made for the LOS model.

In order to account for the effects of topography on transmission loss, the Longley Rice program employs an interdecile range parameter Δh. The computation of Δh requires a digitized terrain data base, but the Longley Rice program itself does not require such a data base. The values of Δh to be used in the military scenario have been computed for the Fulda Gap region of the Federal Republic of Germany by Electromagnetic Compatability

Analysis Center (ECAC). As shown in Figure 2.1, the Link module accesses this Δh data base. Also as shown in Figure 2.1, the Link Module is accessed by the simulation, connectivity, and configuration and routing modules. In both cases, PRSIM read the network links from a file.

E. Connectivity Module

The Connectivity module was used to perform a preliminary connectivity analysis on the terminals defined for each subnetwork and deployment. This module identifies maximal independent subsets of terminals, i.e., subsets of maximal cardinality such that for any PR in a subset there exists a link between that PR and some other PR in the same subset, but no such link exists between that PR and a PR not in the subset. In order to determine connectivity matrices, the connectivity module accesses the data base module for PR locations and the link module to determine which pairs of PR's can communicate directly. This module uses a depth first search algorithm, which is described in the Appendix.

This module was extensively employed to determine the connected subsets for networks whose links were determined using the Longley Rice model. The results are described in the Appendix.

F. Configuration and Routing Modules

In the military scenario prepared by MITRE, terminal locations and needlines are specified, but the network configuration and the routing procedures to be used in the PR subnetworks are not defined. The network configuration problem consists basically of three parts:

- Repeater location
- A PRU transmission power specification
- Transmission data rate specification.

The repeater location problem itself consists of the following two subproblems:

- Identification of terminals (defined in the C^2, Field Artillery, and ADA subnetworks) that should also function as repeaters.

- Identification of locations where dedicated repeaters should be placed.

It is assumed that all terminals have the integral relay capability and that there are no additional constraints (in terms of cost or performance) imposed by including this capability.

The number of repeaters required is primarily a function of the survivability criteria, as well as the PR network delay-throughput requirements. The survivability criteria require that at least k node-disjoint paths exist between any two terminals that must communicate; k is a parameter to be determined. The repeater location problem must be solved in conjunction with a definition of the routing procedures within the network. Additional repeaters may be required to provide additional communication paths in order to eliminate congestion. The point-to-point routing procedure defined in the test bed Channel Access Program 4.6 was employed. Hence, the routing problem consists of:

- Defining primary communications paths through the network for each needline.

- Defining good neighbors to be used in alternate routing.

The other parameters of the network configuration problem PR transmission power level and transmission data rate are also intimately related to the routing problem. The power levels and data rates currently used in the DARPA test bed were used in this study. Both terminals and dedicated repeaters operate at 100 Kbps even when they are functioning as repeaters. The appropriate power level is included in the threshold values specified by CORADCOM for determining connectivity.

Because of the substantial connectivity in the PR networks studied, dedicated repeaters were not required in the simulation. Also the projected traffic loads were very light, hence shortest path routing was found to be acceptable. The shortest path routing procedures were included in the scenario generator. For the host configuration with links determined by the Longley Rice model, a special procedure was devised to select a shortest path that minimizes congestion. This special procedure is described in Section 6.

Because of the simplicities introduced by using LOS links, the configuration, routing and scenario generation programs were combined into a single module. Thus, the combined

output of the Scenario Generator and Routing modules consisted of the traffic profile with the assigned route for each particular message.

2.2. Data Base

The Data Base module consists of three files which contain information exclusively derived from values provided by MITRE in their recommended military scenario. The only preprocessing that will be done is a minimal amount of algebraic transformations done for convenience. The information supplied consisted of:

- The three Command and Control (C^2), Field Artillery, and Air Defense (ADA) traffic matrices.

- Nodal location coordinates, initially, along Defense Line ALPHA, and along Defense Line BRAVO.

- *Tracks for mobile devices.*

The data base module is comprised of three parts subsequently referred to as:

- Terminal location data base.

- Traffic data base.

- Mobility data base.

These data bases are described below.

2.2.1 Terminal Location Data Base

The Terminal Location Data Base, stored on a data file, contains the location of each PR comprising a scenario. The accessing module reads the file and identifies the location of a PR unit for the particular scenario being simulated. The Terminal Location Data Base file contains the following information for each packet radio unit:

- Subnet indicator

- Identifying packet radio number

- Identifying acronym

- Identifying description

- Antenna height

- Location (X-Y coordinates) for each applicable deployment of the three specified. Some units are lost, captured, or destroyed and are thus included only in one or two deployments.

For the Command and Control, Field Artillery, and Air Defense subnetworks, the above information is included in Tables 2.1, 2.2, and 2.3, respectively.

The subnetwork identifier is a 3-character binary variable where:

- The first character is 1 if the corresponding PRU is in the C^2 subnetwork; zero otherwise.

- The second character is 1 if the corresponding PRU is in the Field Artillery subnetwork; zero otherwise.

- The third character is 1 if the corresponding PRU is in the ADA subnetwork; zero otherwise.

For example, if the PRU identifier is 110, the PRU is in the C^2 and Field Artillery subnetworks, but not in the ADA subnetwork. The identifying PRU number is a unique number associated with PRU and corresponds to Table I in the MITRE report [1]. Specifically, PRU j in the data base is the j^{th} entry in Table I. The identifying acronym will be used by the other software modules in identifying PRU's, while the identifying description provides more detailed information to be used in relating the unit to the terminology employed in the MITRE report. The antenna height is included for use in the Longley Rice transmission model; CORADCOM specified the following antenna heights:

TABLE 2.1: C^2 MATRIX PRU LOCATIONS

ID	No.	Acronym	Matrix Entry	Antenna Height	Initial		DL Alpha		DL Bravo	
					Deployment					
110	1	52MECHCP	DIVISION MAIN	2.0	359	269	297	268	131	246
110	2	1BDE	BRIGADE 1	2.0	552	398	504	412	409	420
110	3	2BDE	BRIGADE 2	2.0	545	274	458	267	307	255
110	4	3BDE	BRIGADE 3	2.0	528	142	414	133	302	117
100	5	MNBN1-77IN	MANEUVER BN BDE 1	2.0	597	455	546	459	507	426
100	6	MNBN1-78IN	MANEUVER BN BDE 1	2.0	644	401	563	415	397	119
100	7	MNBN1-79IN	MANEUVER BN BDE 2	2.0	669	326	555	334	452	331
100	8	MNBN1-80IN	MANEUVER BN BDE 2	2.0	606	245	542	276	378	274
100	9	MNBN1-81IN	MANEUVER BN BDE 1	2.0	654	364	551	366	481	377
100	10	MNBN1-82IN	MANEUVER BN BDE 3	2.0	592	132	485	097	400	076
100	11	MNBN1-2AR	MANEUVER BN BDE 3	2.0	599	078	492	138	382	158
100	12	MNBN1-3AR	MANEUVER BN BDE 2	2.0	628	291	538	246		
100	13	MNBN1-4AR	MANEUVER BN BDE 3	2.0	609	185	508.	195		
100	14	MNBN1-5AR	MANEUVER BN BDE 3	2.0	621	217	516	224		
100	15	1-23CAVSQD	CAVALRY SQD	2.0	699	479	699	479	375	210
100	16	AVN BN	AVIATION BN	2.0	349	289	304	236	117	247
100	17	ENG BN	ENGINEER BN	2.0	420	206	338	235	129	232
100	18	CEWI BN	CEWI BN	2.0	352	283	315	265	131	254
100	19	MP CO	MILITARY PO.CO	2.0	372	253	314	251	124	239
100	20	DISCOM	DIV.SUPPORT COM	2.0	325	245	267	260	094	261
100	21	MAINTBN	MAINTENANCE BN	2.0	291	281	274	264	087	256
100	22	MED BN	MEDICAL BN	2.0	355	262	284	248	103	255
100	23	S&T BN	SUPPLY AND TRANS BN	2.0	325	265	278	272	084	263
100	24	AGCO	ADJUTANT GENERAL	2.0	322	238	262	265	094	253
100	25	FINCO	FINANCE CO	2.0	307	255	256	263	097	264
110	26	DIVARTY	DIVISION ARTILLERY	2.0	391	308	306	254	153	260
110	83	DSBN1-40	DIRECT SUPPORT BN1	2.0	581	415	511	408	426	407
110	84	DSBN1-41	DIRECT SUPPORT BN2	2.0	576	275	480	269	327	246
110	85	DSBN1-42	DIRECT SUPPORT BN3	2.0	547	147	445	150	326	113
110	86	GSBN1-43	GENERAL SUPPORT BN	2.0	452	242	356	246	164	268
110	87	70FAGP	FIELD ARTILLERY GP	2.0	362	324	307	279	144	269
110	88	DSR2-631	REINFORCING BN 1	2.0	576	425	504	394	429	431
110	89	DER2-637	REINFORCING BN 2	2.0	575	302	499	288	331	266
110	90	DSR2-638	REINFORCING BN 3	2.0	541	161	438	115	331	135
110	91	GSR2-618	GENERL SUPRT REIN BN	2.0	472	278	358	269	181	295
101	116	ADABN1-441	AIR DEFENSE BN	2.0	397	278	353	284	117	238

TABLE 2.2: FIELD ARTILLERY MATRIX PRU LOCATIONS

					Deployment					
ID	No.	Acronym	Matrix Entry	Antenna Height	Initial		DL Alpha		DL Bravo	
110	1	DIV MAIN	DIVISION FSE	2.0	359	269	297	268	131	246
110	2	1BDE	BRIGADE 1	2.0	552	398	504	412	409	420
110	3	2BDE	BRIGADE 2	2.0	545	274	458	267	307	255
110	4	3BDE	BRIGADE 3	2.0	528	142	414	133	302	117
110	26	DA	DIVISION ARTILLERY	2.0	391	308	306	254	153	260
010	27	TAB	TARGET ACQUSTON BAT	2.0	405	245	342	246	184	270
010	28	DA-SURV 1	DA SURVEY SEC 1	2.0	401	295	313	280	177	298
010	29	DA-SURV 2	DA SURVEY SEC 2	2.0	400	245	334	236	186	268
010	30	SIF CC 2	SIF CONTROL CENTER	2.0	631	392	558	387	477	364
010	31	SIF CC 1	SIF CONTROL CENTER	2.0	608	175	501	161		
010	32	TPS25/58	GROUND SURVEY RADAR	2.0	659	209	548	273		
010	33	TPQ36-1	COUNTER MORTAR 1	2.0	635	418	552	399	452	393
010	34	TPQ36-2	COUNTER MORTAR 2	2.0	621	286	523	260	373	267
010	35	TPQ36-3	COUNTER MORTAR 3	2.0	578	144	486	146	352	117
010	36	TPQ37-1	COUNTER BATTERY 1	2.0	588	373	486	389	424	427
010	37	TPQ37-2	COUNTER BATTERY 2	2.0	533	177	412	163	317	132
010	38	1-GMD-1	GROUND MET DET 1	2.0	662	359	561	376	475	380
010	39	GMD-2	GROUND MET DET 2	2.0	598	608	496	175		
010	40	RPV GCS BN	BN REMT PIL VEH GCS1	2.0	555	386	520	414	406	417
010	41	RPV-GCSBN2	BN REMT PIL VEH GCS2	2.0	544	283	467	272	317	252
010	42	RPV-GCSBN3	BN REMT PIL VEH GCS3	2.0	533	135	423	133	308	114
010	43	RPV-GCS DA	DA REMT PIL VEH GCS1	2.0	396	311	252	317	173	254
010	44	RPV-GCSFSE	FSE REMT PIL VEH 1	2.0	378	272	288	262	149	232
010	45	DA SOTAS	DA SOTAS	2.0	392	303	295	250	155	266
010	46	FSE SOTA	FSE SOTAS	2.0	362	265	296	275	138	246
010	47	1-40 SURV1	BN1 SURV 1 1-40	2.0	605	429	531	429	451	409
010	48	1-40 SURV2	BN1 SURV 2 1-40	2.0	592	392	528	380	436	379
010	49	1-41 SURV1	BN2 SURV 1 1-41	2.0	598	317	521	299	356	276
010	50	1-41 SURV2	BN2 SURV 2 1-41	2.0	572	251	498	254	337	234
010	51	1-42 SURV1	BN3 SURV 1 1-41	2.0	532	177	463	158	359	139
010	52	1-42 SURV2	BN3 SURV 2 1-41	2.0	565	135	456	113	340	092
010	53	FO A/1-401	FORWARD OBS 1	1.5	684	466	591	475	533	460
010	54	FO A/1-402	FORWARD OBS 2	1.5	682	452	591	455	538	423
010	55	FO A/1-403	FORWARD OBS 3	1.5	660	450	584	438	521	406
010	56	FO B 1-401	FORWARD OBS 4	1.5	660	424	583	426	513	383
010	57	FO B 1-402	FORWARD OBS 5	1.5	668	417	592	420	485	351
010	58	FO B 1-403	FORWARD OBS 6	1.5	678	408	597	403	463	329
010	59	FO C 1-401	FORWARD OBS 7	1.5	693	383	598	396	454	305
010	60	FO C 1-402	FORWARD OBS 8	1.5	685	372	592	578		
010	61	FO C 1-403	FORWARD OBS 9	1.5	693	355	594	353	433	287
010	62	FO A 1-411	FORWARD OBS 10	1.5	672	330	593	330	409	247
010	63	FO A 1-412	FORWARD OBS 11	1.5	686	326	588	317	405	222
010	64	FO A 1-413	FORWARD OBS 12	1.5	669	298	591	297	407	191
010	65	FO B 1-411	FORWARD OBS 13	1.5	664	285	583	281	417	164
010	66	FO B 1-412	FORWARD OBS 14	1.5	665	274	576	266	418	148
010	67	FO B 1-413	FORWARD OBS 15	1.5	668	264	571	256		
010	68	FO C 1-411	FORWARD OBS 16	1.5	654	250				
010	69	FO C 1-412	FORWARD OBS 17	1.5	656	230	544	235		
010	70	FO C 1-413	FORWARD OBS 18	1.5	661	214	552	227		
010	71	FO A 1-421	FORWARD OBS 19	1.5	644	198	540	203		

TABLE 2.2: FIELD ARTILLERY MATRIX PRU LOCATIONS (CONTINUED)

ID	No.	Acronym	Matrix Entry	Antenna Height	Deployment Initial		DL Alpha		DL Bravo	
010	72	FO A 1-422	FORWARD OBS 20	1.5	630	177	536	185		
010	73	FO A 1-423	FORWARD OBS 21	1.5	628	160	533	176		
010	74	FO B 1-421	FORWARD OBS 22	1.5	629	151	529	148		
010	75	FO B 1-422	FORWARD OBS 23	1.5	622	133	532	139		
010	76	FO B 1-423	FORWARD OBS 24	1.5	624	119				
010	77	FO C 1-421	FORWARD OBS 25	1.5	642	098	528	118	421	137
010	78	FO C 1-422	FORWARD OBS 26	1.5	629	088	519	101	412	114
010	79	FO C 1-423	FORWARD OBS 27	1.5	635	075	503	076	414	093
010	80	AO BN 1-40	BN1 AERIAL OBSERVR	1.5	620	420	586	410		
010	81	AO BN 1-41	BN2 AERIAL OBSERVR	1.5	620	280	560	270		
010	82	AO BN 1-42	BN3 AERIAL OBSERVR	1.5	580	150	500	090		
110	83	DS BN 1-40	DIRECT SUPPORT BN1	2.0	581	415	511	408	426	407
110	84	DS BN 1-41	DIRECT SUPPORT BN2	2.0	576	275	480	269	327	246
110	85	DS BN 1-42	DIRECT SUPPORT BN3	2.0	547	147	445	150	326	113
110	86	GS BN 1-43	GENERAL SUPPORT BN	2.0	452	242	356	246	164	268
110	87	FA GP	FIELD ARTILLERY GP	2.0	362	324	307	279	144	269
110	88	DSR2-631	DS REINFORC BN 1	2.0	576	425	504	394	429	431
110	89	DSR2-637	DS REINFORC BN 2	2.0	575	302	499	288	331	266
110	90	DSR2-638	DS REINFORC BN	2.0	541	161	438	115	331	135
110	91	GSR2-618	DS GEN SUPP BN	2.0	472	278	358	269	181	295
010	92	BCS1-40 A	DS BAT COM SYS BN1	2.0	618	448	527	437	449	412
010	93	BCS1-40 B	DS BAT COM SYS BN1	2.0	627	426	530	374	441	393
010	94	BCS1-40 C	DS BAT COM SYS BN1	2.0	626	397				
010	95	BCS1-41 A	DS BAT COM SYS BN2	2.0	612	315	522	296	351	248
010	96	BCS1-41 B	DS BAT COM SYS BN2	2.0	606	275	511	267	336	205
010	97	BCS1-41 C	DS BAT COM SYS BN2	2.0	601	242	493	235		
010	98	BCS1-42 A	DS BAT COM SYS BN3	2.0	577	176	469	178		
010	99	BCS1-42 B	DS BAT COM SYS BN3	2.0	564	148	466	158	346	114
010	100	BCS1-42 C	DS BAT COM SYS BN3	2.0	567	116	453	123	349	094
010	101	BCS1-43 A	GS BAT COM SYS BN	2.0	492	266	390	245	230	299
010	102	BCS1-43 B	GS BAT COM SYS BN	2.0	475	233	369	226	211	258
010	103	BCS1-43 C	GS BAT COM SYS BN	2.0	475	208	349	199	206	195
010	104	BCS2-631A	RDS BAT COM SYS BN1	2.0	617	465	524	427	451	458
010	105	BCS2-631B	RDS BAT COM SYS BN1	2.0	618	434	535	404	449	435
010	106	BCS2-631C	RDS BAT COM SYS BN1	2.0	617	403	526	383	449	411
010	107	BCS2-637A	RDS BAT COM SYS BN2	2.0	621	332	517	315		
010	108	BCS2-637B	RDS BAT COM SYS BN2	2.0	607	293	518	278	410	312
010	109	BCS2-637C	RDS BAT COM SYS BN2	2.0	579	237	499	252	375	278
010	110	BCS2-638A	RDS BAT COM SYS BN3	2.0	561	198	455	138	360	163
010	111	BCS2-638B	RDS BAT COM SYS BN3	2.0	569	166	457	104	365	141
010	112	BCS2-638C	RDS BAT COM SYS BN3	2.0	560	127	437	079	364	125
010	113	BCS2-618A	RGS BAT COM SYS RGS1	2.0	498	325	416	318	254	332
010	114	BCS2-618B	RGS BAT COM SYS RGS1	2.0	480	313	419	299	212	276
010	115	BCS2-618C	RGS BAT COM SYS RGS1	2.0	495	284	399	272	206	235

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TABLE 2.3: ADA MATRIX PRU LOCATIONS

ID	No.	Acronym	Matrix Entry	Antenna Height	Deployment					
					Initial		DL Alpha		DL Bravo	
101	116	1-441 CVBN	C/V BN	2.0	397	278	353	284	117	238
001	117	A/1CV BTRY	C/V BATTERY	2.0	365	269	286	272	120	247
001	118	B/1CV BTRY	C/V BATTERY	2.0	459	239	378	272	161	272
001	119	C/1CV BTRY	C/V BATTERY	2.0	525	138	464	263	323	249
001	120	D/1CV BTRY	C/V BATTERY	2.0	557	273	420	132	330	127
001	121	1/A/C PLN	C/V PLATOON 1	2.0	371	260	310	278	092	262
001	122	2/A/C PLN	C/V PLATOON 2	2.0	355	289	278	258	127	232
001	123	3/A/V PLN	C/V PLATOON 3	2.0	367	269	293	273	131	251
001	124	1/B/C PLN	C/V PLATOON 4	2.0	496	322	403	275	235	287
001	125	2/B/CVPLN	C/V PLATOON 5	2.0	481	209	418	320	206	233
001	126	3/B/CVPLN	C/V PLATOON 6	2.0	469	280	355	243	178	295
001	127	1/C/CVPLN	C/V PLATOON 7	2.0	575	179	492	287	329	263
001	128	2/C/CVPLN	C/V PLATOON 8	2.0	530	142	477	269	324	239
001	129	3/C/VPLN	C/V PLATOON 9	2.0	565	117	452	265	303	251
001	130	1/D/CVPLN	C/V PLATOON 10	2.0	573	299	456	143	328	132
001	131	2/D/CVPLN	C/V PLATOON 11	2.0	548	274	444	113	328	111
001	132	3/D/VPLN	C/V PLATOON 12	2.0	578	240	413	139	301	114
001	133	1CFV/A	FIRING UNIT PH 1	2.0	362	306	322	307	225	316
001	134	2CFV/A	FIRING UNIT PH 1	2.0	345	294	302	301	217	308
001	135	3CFV/A	FIRING UNIT PH 1	2.0	375	286	338	289	238	292
001	136	4CFV/A	FIRING UNIT PH 1	2.0	337	281	281	285	198	273
001	137	5CFV/A	FIRING UNIT PH 2	2.0	395	270	325	262	237	262
001	138	6CFV/A	FIRING UNIT PH 2	2.0	345	268	265	262	195	249
001	139	7CFV/A	FIRING UNIT PH 2	2.0	374	266	312	245	231	218
001	140	8CFV/A	FIRING UNIT PH 2	2.0	365	260	271	237	193	198
001	141	9VFV/A	FIRING UNIT PH 3	2.0	358	274	298	272	181	299
001	142	10VFV/A	FIRING UNIT PH 3	2.0	362	271	301	269	179	293
001	143	11VFV/A	FIRING UNIT PH 3	2.0	356	269	292	268	165	273
001	144	12VFV/A	FIRING UNIT PH 3	2.0	359	267	297	265	165	262
001	145	13CFV/B	FIRING UNIT PH 4	2.0	521	329	423	328	115	280
001	146	14CFV/B	FIRING UNIT PH 4	2.0	529	311	446	310	080	278
001	147	15CFV/B	FIRING UNIT PH 4	2.0	507	299	436	292	129	268
001	148	16CFV/B	FIRING UNIT PH 4	2.0	521	275	409	268	076	265
001	149	17CFV/B	FIRING UNIT PH 5	2.0	513	248	409	247	155	261
001	150	18CFV/B	FIRING UNIT PH 5	2.0	498	227	400	219	085	251
001	151	19CFV/B	FIRING UNIT PH 5	2.0	505	206	392	201	101	233
001	152	20CFV/B	FIRING UNIT PH 5	2.0	502	177	379	183	132	229
001	153	21FCV/B	FIRING UNIT PH 6	2.0	472	285	361	271	132	248
001	154	22VFV/B	FIRING UNIT PH 6	2.0	475	282	359	268	134	245
001	155	23VFV/B	FIRING UNIT PH 6	2.0	455	244	358	246	129	244
001	156	24VFV/B	FIRING UNIT PH 6	2.0	454	242	360	244	131	242
001	157	25CFV/C	FIRING UNIT PH 7	2.0	602	193	501	291	334	268
001	158	26CFV/C	FIRING UNIT PH 7	2.0	607	178	498	286	331	264
001	159	27CFV/C	FIRING UNIT PH 7	2.0	588	108	482	273	306	259
001	160	28CFV/C	FIRING UNIT PH 7	2.0	576	085	459	272	312	255
001	161	29VFV/C	FIRING UNIT PH 8	2.0	579	179	479	268	303	255
001	162	30VFV/C	FIRING UNIT PH 8	2.0	579	174	461	265	307	251
001	163	31VFV/C	FIRING UNIT PH 8	2.0	524	146	456	263	329	248
001	164	32VFV/C	FIRING INIT PH 8	2.0	533	144	462	271	326	243
001	165	33VFV/C	FIRING UNIT PH 9	2.0	522	140	509	291	396	304

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TABLE 2.3: ADA MATRIX PRU LOCATIONS (CONT.)

ID	No.	Acronym	Matrix Entry	Antenna Height	Deployment Initial		DL Alpha		DL Bravo	
001	166	34VFV/C	FIRING UNIT PH 9	2.0	523	133	500	282	381	275
001	167	35VFV/C	FIRING UNIT PH 9	2.0	570	117	487	265	373	238
001	168	36VFV/C	FIRING UNIT PH 9	2.0	566	114	474	255	371	198
001	169	37VFV/D	FIRING UNIT PH 10	2.0	575	303	448	152	331	137
001	170	38VFV/D	FIRING UNIT PH 10	2.0	575	298	443	148	333	130
001	171	39VFV/D	FIRING UNIT PH 10	2.0	552	281	412	137	304	119
001	172	40VFV/D	FIRING UNIT PH 10	2.0	547	277	415	136	308	117
001	173	41VFV/D	FIRING UNIT PH 11	2.0	546	270	411	131	328	116
001	174	42VFV/D	FIRING UNIT PH 11	2.0	552	269	417	131	296	115
001	175	43VFV/D	FIRING UNIT PH 11	2.0	582	240	442	119	323	111
001	176	44VFV/D	FIRING UNIT PH 11	2.0	582	235	439	111	301	111
001	177	45CFV/D	FIRING UNIT PH 12	2.0	586	318	469	160	376	157
001	178	46CFV/D	FIRING UNIT PH 12	2.0	53	289	469	142	366	138
001	179	47CFV/D	FIRING UNIT PH 12	2.0	582	261	463	115	358	118
001	180	48CFV/D	FIRING UNIT PH 12	2.0	578	224	462	090	349	102
001	181	1 FAAR	FRWRDAREA ALRTRADR1	2.0	647	459	579	462	520	418
001	182	2 FAAR	FRWRDAREA ALRTRADR2	2.0	661	395	582	386	446	311
001	183	3 FAAR	FRWRDAREA ALRTRADR3	2.0	628	318	575	325	402	268
001	184	4 FAAR	FRWRDAREA ALRTRADR4	2.0	625	268	544	283	391	201
001	185	5 FAAR	FRWRDAREA ALRTRADR5	2.0	638	208	539	242		
001	186	6 FAAR	FRWRDAREA ALRTRADR6	2.0	617	161	535	183		
001	187	7 FAAR	FRWRDAREA ALRTRADR7	2.0	608	127	519	137		
001	188	8 FAAR	FRWRDAREA ALRTRADR8	2.0	628	089	502	089	388	104
001	189	1-451 IH	IMPROVED HAWK TSQ73	2.0	408	287	305	316	127	214
001	190	A/IH BTRY	IMPROVED HAWK BTRY1	2.0	515	434	415	433	276	417
001	191	B/IH BTRY	" " " 2	2.0	422	328	398	301	228	199
001	192	C/IH BTRY	" " " 3	2.0	477	196	354	166	205	113
001	193	1FU/1-451	" " FU 1	2.0	520	439	424	428	292	424
001	194	2FU/1-451	" " " 2	2.0	508	436	423	436	278	409
001	195	3FU/1-451	" " " 3	2.0	514	428	423	419	289	403
001	196	4FU/1-451	" " " 4	2.0	429	339	397	311	241	206
001	197	5FU/1-451	" " " 5	2.0	425	335	392	303	239	203
001	198	6FU/1-451	" " " 6	2.0	428	331	390	299	235	195
001	199	7FU/1-451	" " " 7	2.0	481	202	357	194	219	131
001	200	8FU/1-451	" " " 8	2.0	467	190	354	188	213	118
001	201	9FU/1-451	" " " 9	2.0	475	183	355	179	208	106
001	202	1RE/1-77	REDEYE 1	1.0	629	458	587	473	535	423
001	203	2RE/1-77	" 2	1.0	647	443	572	461	504	419
001	204	3RE/1-77	" 3	1.0	644	427	548	459	511	417
001	205	4RE/1-77	" 4	1.0	642	417	584	457	522	409
001	206	5RE/1-77	" 5	1.0	600	458	582	437	507	396
001	207	6RE/1-77	" 6	1.0	645	404	581	419	417	128
001	208	7RE/1-77	" 7	1.0	652	397	568	414	401	119
001	209	8RE/1-78	" 8	1.0	667	379	569	405	397	113
001	210	9RE/1-78	" 9	1.0	635	394	595	404	404	107
001	211	10RE/1-78	" 10	1.0	699	479	699	479	404	210
001	212	11RE/1-78	" 11	1.0	677	327				
001	213	12RE/1-79	" 12	1.0	672	318	559	334	470	335
001	214	13RE/1-79	" 13	1.0	659	339	566	326	456	326
001	215	14RE/1-79	" 14	1.0	664	309	585	320	449	318

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TABLE 2.3: ADA MATRIX PRU LOCATIONS (CONT.)

ID	No.	Acronym	Matrix Entry		Antenna Height	Deployment Initial		DL Alpha		DL Bravo	
001	216	15RE/1-79	"	15	1.0	659	280	566	255		
001	217	16RE/1-80	"	16	1.0	641	255	579	278	384	270
001	218	17RE/1-80	"	17	1.0	633	228	550	224		
001	219	18RE/1-80	"	18	1.0	612	243	564	275	394	265
001	220	19RE/1-80	"	19	1.0	631	250	546	282	403	243
001	221	20RE/1-80	"	20	1.0	640	246	575	270	401	226
001	222	21RE/1-80	"	21	1.0	675	368	589	373	485	376
001	223	22RE/1-81	"	22	1.0	669	354	554	365	507	373
001	224	23RE/1-81	"	23	1.0	657	363	572	365	488	372
001	225	24RE/1-81	"	24	1.0	669	406	585	365	485	353
001	226	25RE/1-81	"	25	1.0	678	379				
001	227	26RE/1-23	"	26	1.0	680	454			379	205
001	228	27RE/1-23	"	27	1.0	371	238			402	185
001	229	28RE/1-23	"	28	1.0	365	247			407	174
001	230	29RE/1-23	"	29	1.0	629	470			501	476
001	231	30RE/1-23	"	30	1.0	594	475			527	452
001	232	31RE/1-82	"	31	1.0	620	146	501	075	414	085
001	233	32RE/1-82	"	32	1.0	629	165	532	173		
001	234	33RE/1-82	"	33	1.0	602	141	501	100	405	076
001	235	34RE/1-82	"	34	1.0	595	132	493	098	393	073
001	236	35RE/1-82	"	35	1.0	608	128	513	097	423	072
001	237	36RE/1-2	"	36	1.0	613	071	525	148		
001	238	37RE/1-2	"	37	1.0	601	079	508	145	407	160
001	239	38RE/1-2	"	38	1.0	614	079	502	135	393	160
001	240	39RE/1-2	"	39	1.0	626	074	524	133	384	156
001	241	40RE/1-2	"	40	1.0	374	219	406	262		
001	242	41RE/1-3	"	41	1.0	669	338	585	304	455	312
001	243	42RE/1-3	"	42	1.0	663	294	552	251		
001	244	43RE/1-3	"	43	1.0	630	289	558	249		
001	245	44RE/1-3	"	44	1.0	657	266	542	245		
001	246	45RE/1-3	"	45	1.0	646	275	558	238		
001	247	46RE/1-4	"	46	1.0	646	201	519	120	395	067
001	248	47RE/1-4	"	47	1.0	626	198	538	204		
001	249	48RE/1-4	"	48	1.0	609	188	512	195		
001	250	49RE/1-4	"	49	1.0	629	178	519	189		
001	251	50RE/1-4	"	50	1.0	598	107	536	189		
001	252	51RE/1-5	"	51	1.0	613	245	585	288	416	283
001	253	52RE/1-5	"	52	1.0	637	237	555	230		
001	254	53RE/1-5	"	53	1.0	625	220	519	224		
001	255	54RE/1-5	"	54	1.0	636	223	540	222		
001	256	55RE/1-5	"	55	1.0	639	216	549	217		
001	257	56RE/1-40	"	56	1.0	623	448	530	438	427	402
001	258	57RE/1-40	"	57	1.0	631	428	513	409	442	393
001	259	58RE/1-40	"	58	1.0	589	412	538	397	443	371
001	260	59RE/1-40	"	59	1.0	632	398				
001	261	60RE/1-41	"	60	1.0	616	314	530	298	332	252
001	262	61RE/1-41	"	61	1.0	580	277	485	271	358	247
001	263	62RE/1-41	"	62	1.0	613	275	518	267	342	197
001	264	63RE/1-41	"	63	1.0	606	239	497	234		
001	265	64RE/1-42	"	64	1.0	579	176	475	175		

TABLE 2.3: ADA MATRIX PRU LOCATIONS (CONT.)

ID	No.	Acronym	Matrix Entry		Antenna Height	Deployment Initial		DL Alpha		DL Bravo	
001	266	65RE/1-42	"	65	1.0	569	149	462	157	354	115
001	267	66RE/1-42	"	66	1.0	549	147	447	148	330	114
001	268	67RE/1-42	"	67	1.0	573	114	455	127	346	095
001	269	68RE/1-43	"	68	1.0	496	267	359	199	235	299
001	270	69RE/1-43	"	69	1.0	455	242	358	246	166	269
001	271	70RE/1-43	"	70	1.0	482	234	395	242	214	258
001	272	71RE/1-43	"	71	1.0	482	209	375	226	214	194
001	273	72RE/2-631	"	72	1.0	622	464	526	427	453	459
001	274	73RE/2-631	"	73	1.0	622	430	536	405	452	436
001	275	74RE/2-631	"	74	1.0	581	425	507	396	435	433
001	276	75RE/2-631	"	75	1.0	625	404	532	383	457	413
001	277	76RE/2-637	"	76	1.0	626	330	524	314		
001	278	77RE/2-637	"	77	1.0	578	302	505	287	414	310
001	279	78RE/2-637	"	78	1.0	609	292	523	277	379	277
001	280	79RE/2-637	"	79	1.0	583	238	506	250	333	263
001	281	80RE/2-638	"	80	1.0	566	197	455	127	364	163
001	282	81RE/2-638	"	81	1.0	574	169	422	115	367	139
001	283	82RE/2-638	"	82	1.0	543	162	464	103	335	136
001	284	83RE/2-638	"	83	1.0	563	124	445	078	367	124
001	285	84RE/2-618	"	84	1.0	504	330	421	322	259	329
001	286	85RE/2-618	"	85	1.0	489	314	422	297	183	395
001	287	86RE/2-618	"	86	1.0	500	285	401	272	214	278
001	288	87RE/2-618	"	87	1.0	475	281	362	269	211	236
001	289	88RE/1-451	"	88	1.0	521	434	426	436	279	418
001	290	89RE/1-451	"	89	1.0	432	331	399	307	231	203
001	291	90RE/1-451	"	90	1.0	409	289	357	165	210	115
001	292	91RE/1-451	"	91	1.0	482	195	311	314	130	215
001	293	92RE/1-441	"	92	1.0	405	276	466	257	121	245
001	294	93RE/1-441	"	93	1.0	369	270	425	131	121	236
001	295	94RE/1-441	"	94	1.0	465	238	384	270	165	279
001	296	95RE/1-441	"	95	1.0	534	138	288	274	327	242
001	297	96RE/1-441	"	96	1.0	562	277	355	388	331	124

- REDEYE, 1.5 meters

- Forward observers, 1.0 meters

- All other units, 2 meters.

The coordinates included in the Data Base are tenths of kilometers from the origin assigned by MITRE. For example, in initial deployment, the 52ND Mechanized Division Support Command (DISCOM) is located at NB325 245. The X and Y coordinates of the PR unit (PRU) is, in this case, 32.5 km and 24.5 km, respectively. Let (X1, Y1) and (X2, Y2) be the coordinates of PRU's N1 and N2, respectively. Then to find the linear distance in kilometers between N1 and N2, the following equation is used:

$$\text{distance between N1 and N2 in km} = \sqrt{\left(\frac{X1 - X2}{10}\right)^2 + \left(\frac{Y1 - Y2}{10}\right)^2}$$

Attrition occurs twice during the 30-hour period. If a PR unit is lost, destroyed, or missing as a result of attrition, its subsequent coordinates are omitted from the Data Base. Also, REDEYE units 26 through 30 are held in reserve during the DL ALPHA hostilities, but return to action for the DL BRAVO deployment. Hence, the coordinates of these units are not included for the DL ALPHA deployment. Thus, the module accessing the location file for any scenario will recognize the blank and consider the Packet Radio unit as not existing in that particular scenario.

2.2.2 Traffic Data Base

The traffic data base contains the traffic data corresponding to each of the three traffic matrices, Command and Control, Field Artillery, and Air Defense, supplied by MITRE.

The MITRE traffic information includes:

- Total number of transmissions during the 30-hour scenario

- Total bits transferred

- Average message lengths

- Busy hour percentage (based on a 24-hour period).

The number of messages transmitted between any two packet radio unit pairs is independent of deployment. Hence, if there are X transmissions per second between packet radio unit A and packet B in the initial deployment, then there are also X transmissions per second between these packet radio units in the Defense Line ALPHA and BRAVO deployments, providing neither unit is lost through attrition. Hence, the overall magnitude of the traffic flows are changed between deployments only due to attrition, not due to any change in requirements. However, due to changes in the routing, some devices could experience an increased loading.

In the traffic matrices supplied by MITRE, each transmitting source and receiving destination are identified by name, e.g., DIV MAIN CP, BDE (3), FO (9). In the case where there are no parentheses following the term, there is only one entity; for example, DIV MAIN CP means that Division Main Command Post is a single entity implying only one PRU (for a particular subnetwork). Each source may comprise a group of PR units, as indicated by the number in parentheses (BDE BN (3), FO (9)). For BDE (3) there are three separate brigades implying three packet radio units, one for each brigade. However for FO (9), there are 9 groups (corresponding to the 9 Battery Computer Systems units) of Forward Observers, each composed of 3 Forward Observers; hence, for FO (9), 27 packet radio units are required.

The functional needlines are depicted in Figures 2.2 through 2.7 for each subnetwork. In Figure 2.2 the complete C^2 subnetwork is depicted with a box associated with each PRU. The information in the box includes the military name or unit number; the number encircled near the box is the unique identifying number from the location data base. A line with an arrow from box A to box B indicates unit A transmits to unit B; in the C^2 subnetwork there are no simplex communications lines, so all lines have arrows on both ends.

The numbers near the arrows indicate the total nuber of transmissions during the 30-hour duration in the direction of the arrow. For the C^2 subnetwork the busy hour percentage is 10% for all needlines.

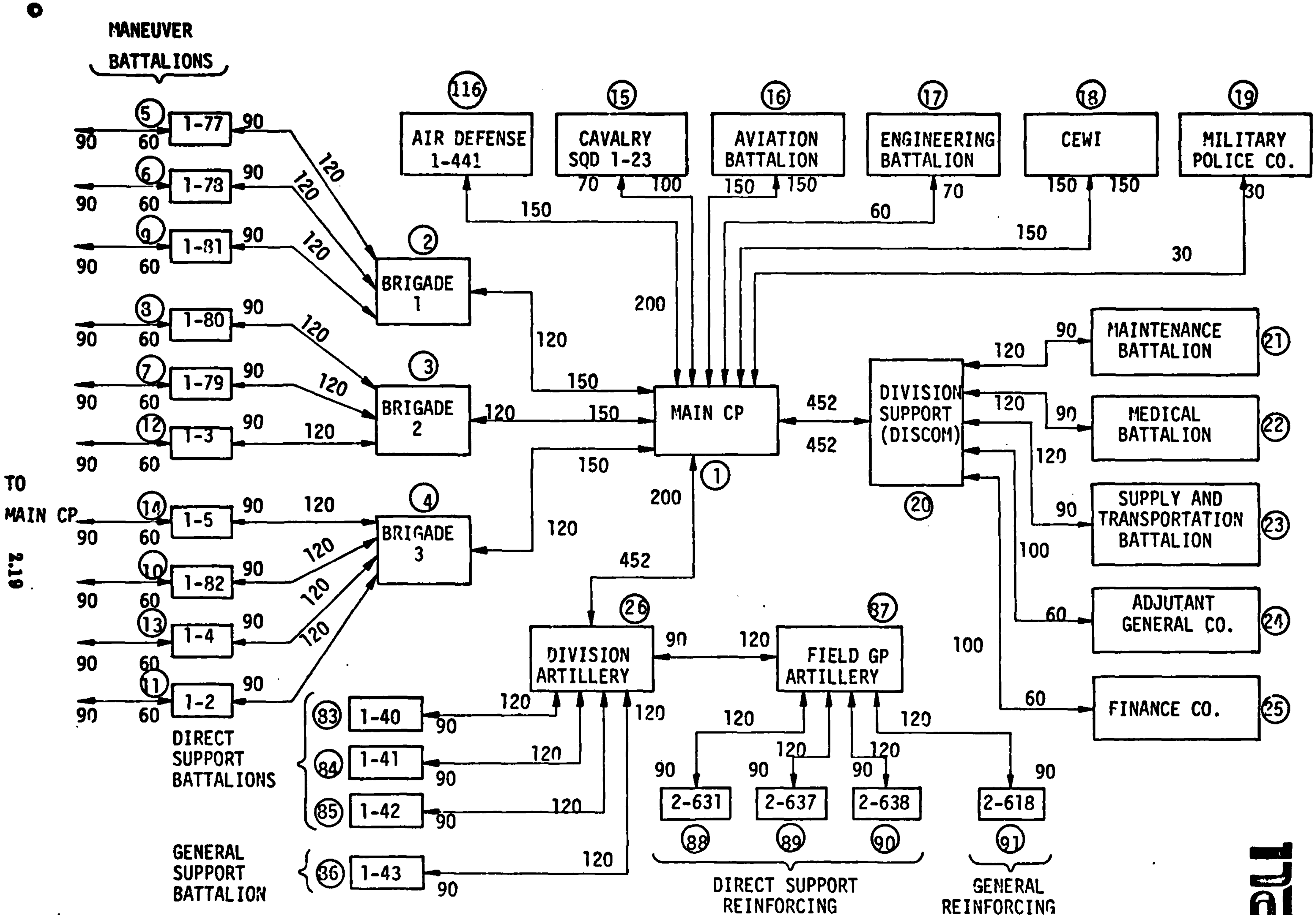

FIGURE 2.2: COMMAND AND CONTROL FUNCTIONAL NEEDLINES

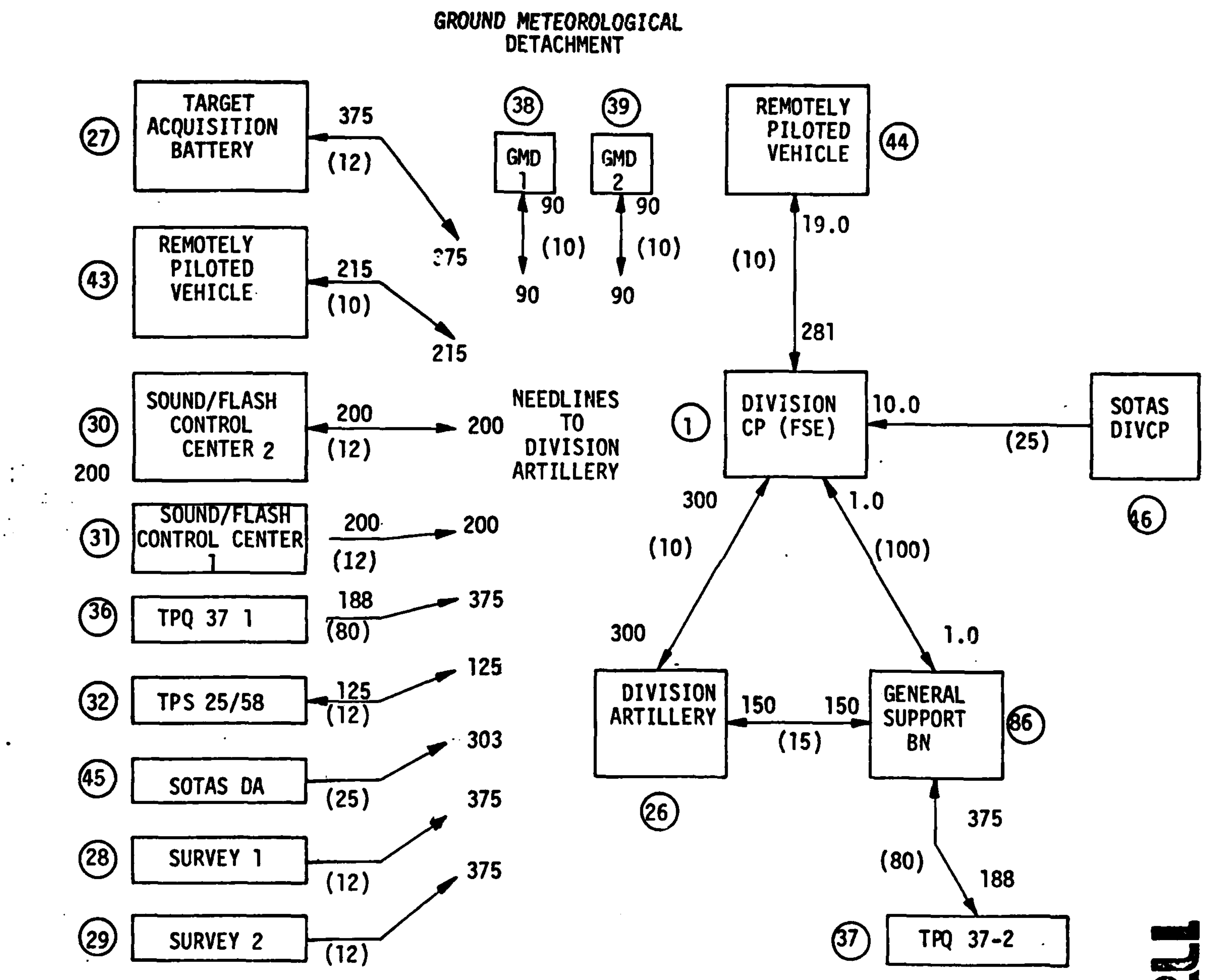

FIGURE 2.3: FIELD ARTILLERY LEVEL 1

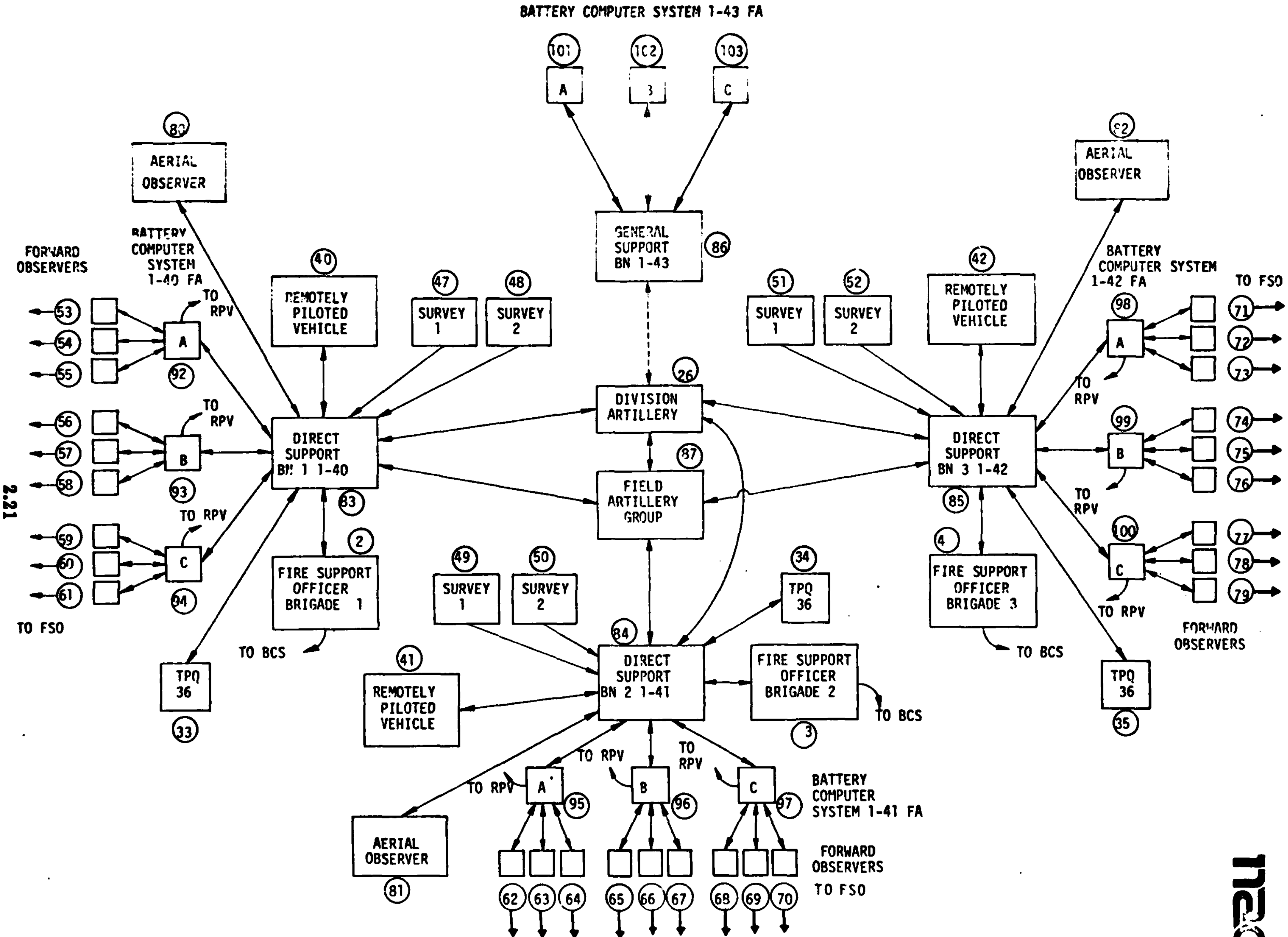

FIGURE 2.4: FIELD ARTILLERY LEVEL 2

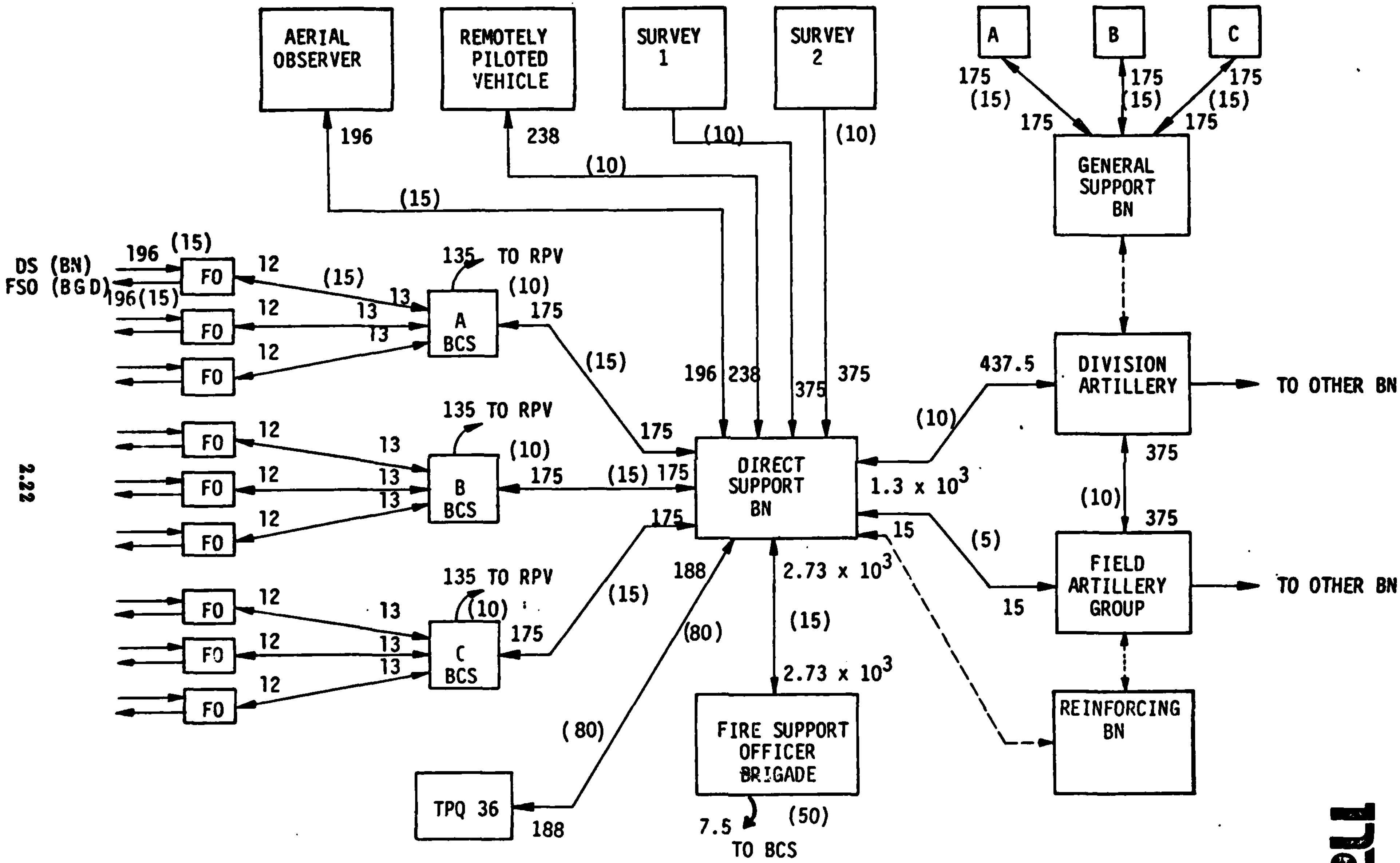

FIGURE 2.5: FIELD ARTILLERY LEVEL 2 NEEDLINES (QUANTITATIVE)

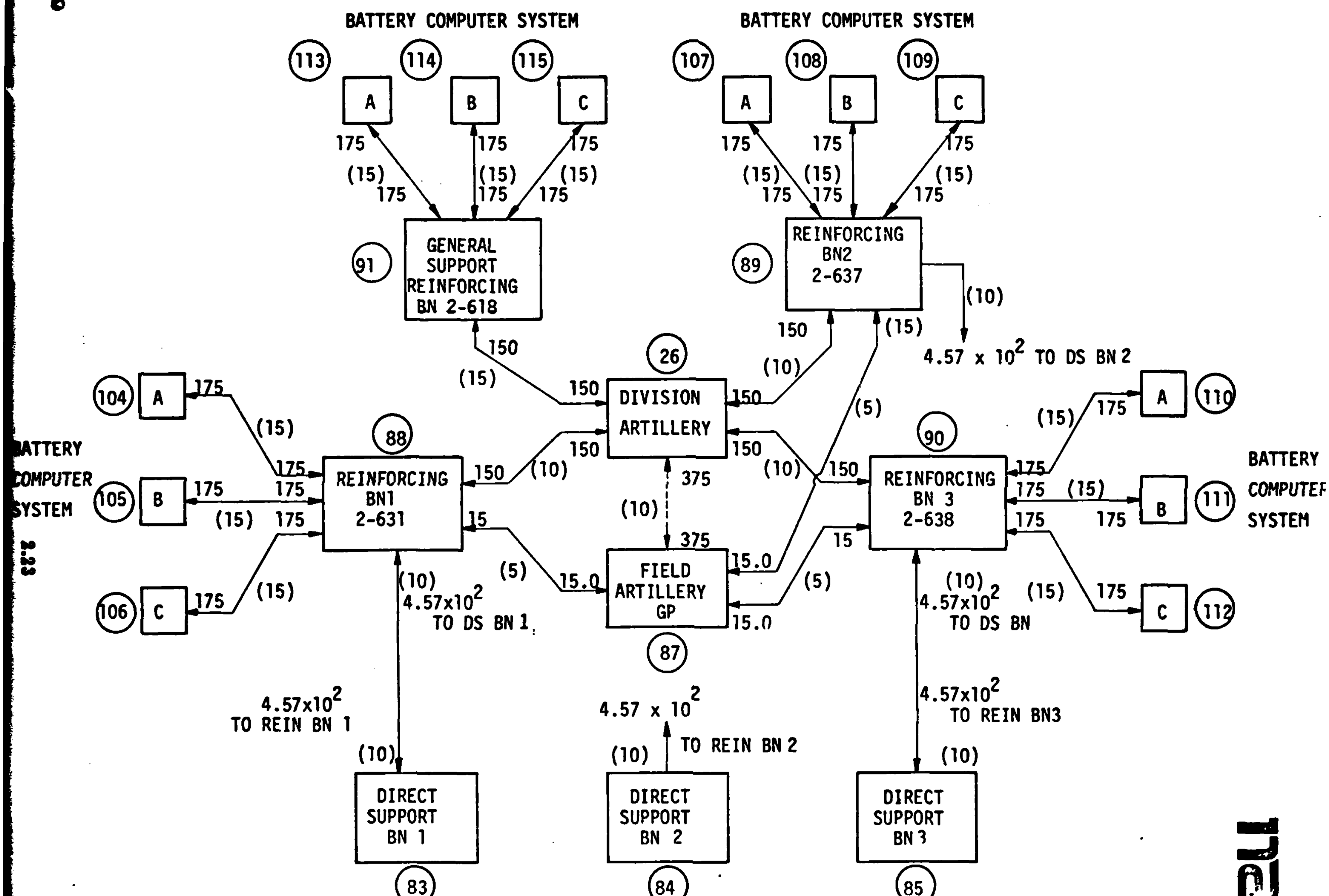

FIGURE 2.6: FIELD ARTILLERY REINFORCING PARTITION

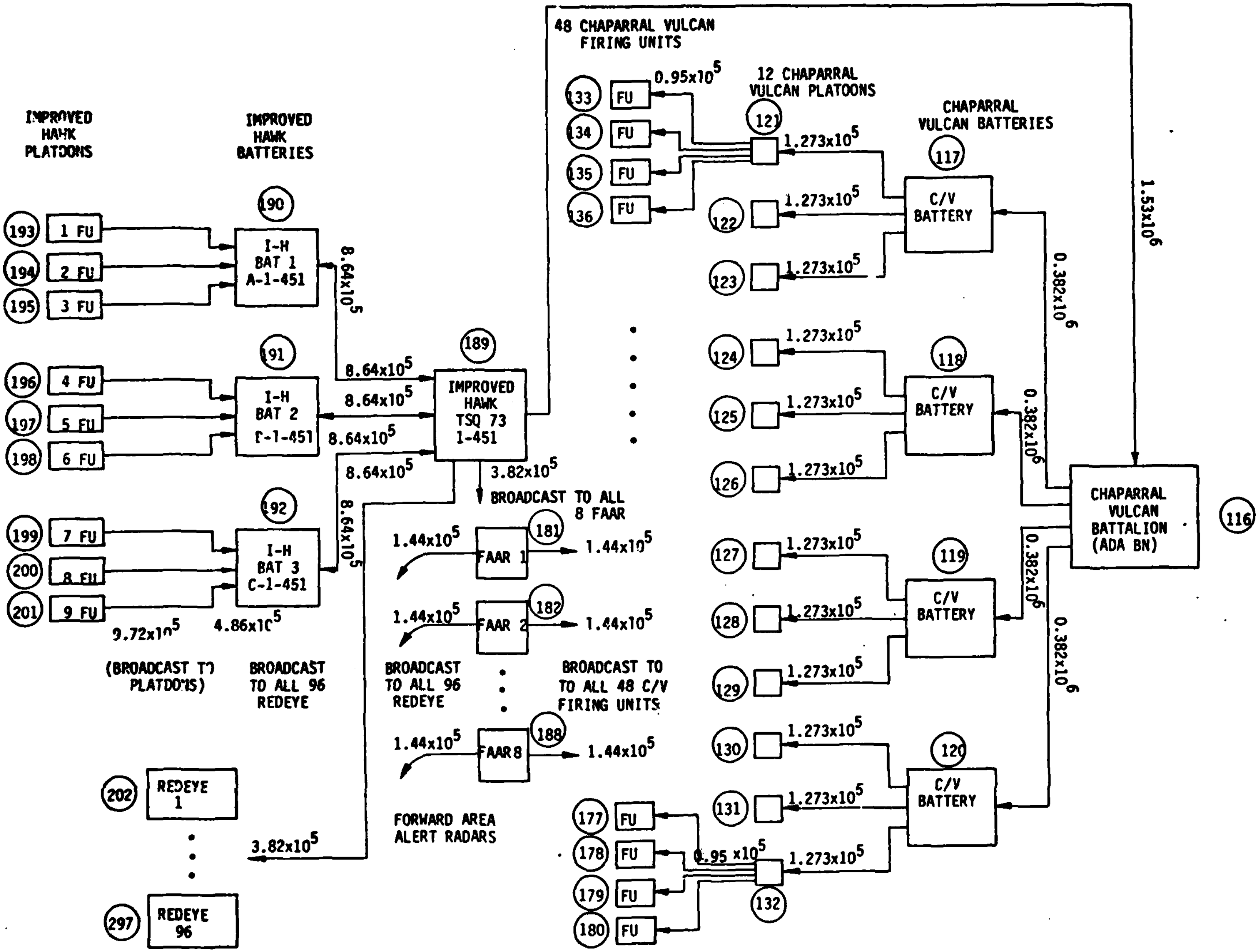

FIGURE 2.7: AIRDEFENSE NEEDLINES

Analogous information is presented for Field Artillery in Figures 2.3 through 2.6. Multiple figures were employed for clarity of presentation, rather than to define further subnetworks at this time. The three levels presented are depicted in Figure 2.3, 2.4, and 2.6, but the numerical values of total number of transmissions were not included in Figure 2.4. Instead, for purposes of clarity, a generic Direct Support Battalion and a single General Support Batallion are depicted in Figure 2.5. With quantitative values for the needlines presented in Figure 2.5, the needlines for Figure 2.4 can be readily deduced.

Since the busy hour percentage is a function of the needline, this percentage is specified in Figures 2.3, 2.5, and 2.6; this is the number in parentheses next to the needline.

In Figure 2.7, the needlines for the entire ADA subnetwork are presented. The major distinguishing characteristics of this subnetwork are:

- Multidestination traffic

- Traffic rate is uniform throughout the 30-hour period; hence, no busy period fraction is specified.

In the computation of the needlines shown in the aforementioned figures, the following convention specified by MITRE has been employed. For single transmitter and receiver the matrix entry provided by MITRE is the point-to-point traffic flow for the 30-hour period. If the transmitting entity is a group with no subgroups, e.g., BDE (3), and the destination is a single unit, then the matrix entry is again the point-to-point traffic. However, if the transmitting entity is composed of a subgroup composed of three FO's, then the matrix entry is the traffic flow from each subgroup to the destination. In this case, the point-to-point traffic flow is computed by dividing by the number of units in a subgroup.

When there are multiple destinations, then the matrix entry is the total number of transmissions to all destinations. Hence, the point-to-point traffic must be computed by dividing the number of destinations.

The traffic data base will contain the following information for each scenario:

- Total number of transmissions over 30-hour period from each military unit to each destination unit, i.e., point-to-point traffic.

- Busy hour traffic percentage, i.e., the percentage of the total 24-hour traffic that occurs during a busy hour; for ADA this value is 100/24.

- Transmitting PRU identifying number.

- Destination PRU identifying number.

- For DL Alpha and DL BRAVO, 1, if the needline is contained in that deployment, and 0 otherwise.

This information is listed in Tables 2.4 and 2.5 for the C^2 and Field Artillery subnetworks, respectively.

2.2.3 Mobility Data Base

This part of the data base applies to mobile PR units and constitutes a location data base for mobile units. It contains:

- The coordinates of the points defining the tracks over which mobile PR units fly. It is assumed that the tracks are in the shape of a quandrangle formed by joining each of a set of coordinates; this is an approximation to a race track pattern.

- The velocity of motion of each mobile PR unit (meters/second).

Figure 2.8 shows the track for mobile units on the south sector where points P_1, P_2, P_3, and P_4 comprise the set of coordinates defining the track. Each side of the quadrangle is divided into shorter lengths of sections (as in Figure 2.8), as defined by a sector length parameter in the data base. This parameter specifies into how many equal length sectors the track should be divided. Clockwise motion is assumed. The mobility data base is listed in Table 2.6 with a default velocity of 60 meters/second and sector parameter of 10. The only scenario with mobile devices is the Field Artillery scenario during the initial deployment.

TABLE 2.4: COMMAND AND CONTROL TRAFFIC DATA BASE

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
120.00	10	1	2	1	1
120.00	10	1	3	1	1
120.00	10	1	4	1	1
60.00	10	1	5	1	1
60.00	10	1	6	1	1
60.00	10	1	7	1	1
60.00	10	1	8	1	1
60.00	10	1	9	1	1
60.00	10	1	10	1	1
60.00	10	1	11	1	1
60.00	10	1	12	1	0
60.00	10	1	13	1	0
60.00	10	1	14	1	0
70.00	10	1	15	1	1
150.00	10	1	16	1	1
70.00	10	1	17	1	1
150.00	10	1	18	1	1
30.00	10	1	19	1	1
452.00	10	1	20	1	1
452.00	10	1	26	1	1
150.00	10	1	116	1	1
150.00	10	2	1	1	1
90.00	10	2	5	1	1
90.00	10	2	6	1	1
90.00	10	2	9	1	1
150.00	10	3	1	1	1
90.00	10	3	7	1	1
90.00	10	3	8	1	1
90.00	10	3	12	1	0
150.00	10	4	1	1	1
90.00	10	4	10	1	1
90.00	10	4	11	1	1
90.00	10	4	13	1	0
90.00	10	4	14	1	0
90.00	10	5	1	1	1
120.00	10	5	2	1	1
90.00	10	6	1	1	1
120.00	10	6	2	1	1
90.00	10	7	1	1	1
120.00	10	7	3	1	1
90.00	10	8	1	1	1
120.00	10	8	3	1	1
90.00	10	9	1	1	1
120.00	10	9	2	1	1
90.00	10	10	1	1	1
120.00	10	10	4	1	1
90.00	10	11	1	1	1
120.00	10	11	4	1	1
90.00	10	12	1	1	0
120.00	10	12	3	1	0
90.00	10	13	1	1	0

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TABLE 2.4: COMMAND AND CONTROL TRAFFIC DATA BASE (CONT.)

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
120.00	10	13	4	1	0
90.00	10	14	1	1	0
120.00	10	14	4	1	0
100.00	10	15	1	1	1
150.00	10	16	1	1	1
60.00	10	17	1	1	1
150.00	10	18	1	1	1
30.00	10	19	1	1	1
452.00	10	20	1	1	1
90.00	10	20	21	1	1
90.00	10	20	22	1	1
90.00	10	20	23	1	1
60.00	10	20	24	1	1
60.00	10	20	25	1	1
120.00	10	21	20	1	1
120.00	10	22	20	1	1
120.00	10	23	20	1	1
100.00	10	24	20	1	1
100.00	10	25	20	1	1
200.00	10	26	1	1	1
90.00	10	26	83	1	1
90.00	10	26	84	1	1
90.00	10	26	85	1	1
30.00	10	26	86	1	1
120.00	10	26	87	1	1
120.00	10	83	26	1	1
120.00	10	84	26	1	1
120.00	10	85	26	1	1
120.00	10	86	26	1	1
90.00	10	87	26	1	1
90.00	10	87	88	1	1
90.00	10	87	89	1	1
90.00	10	87	90	1	1
90.00	10	87	91	1	1
120.00	10	88	87	1	1
120.0	10	89	87	1	1
120.00	10	90	87	1	1
120.00	10	91	87	1	1
200.00	10	116	1	1	1

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TABLE 2.5: FIELD ARTILLERY TRAFFIC DATA BASE

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
19.00	10	1	44	1	1
300.00	10	1	26	1	1
1.00	100	1	86	1	1
2730.00	15	2	83	1	1
7.50	50	2	92	1	1
7.50	50	2	93	1	1
7.50	50	2	94	0	0
2730.00	15	3	84	1	1
7.50	50	3	95	1	1
7.50	50	3	96	1	1
7.50	50	3	97	1	0
2730.00	15	4	85	1	1
7.50	50	4	98	1	0
7.50	50	4	99	1	1
7.50	50	4	100	1	1
150.00	15	26	86	1	1
300.00	10	26	1	1	1
125.00	12	26	32	1	0
188.00	80	26	36	1	1
200.00	12	26	31	1	0
200.00	12	26	30	1	1
215.00	10	26	43	1	1
375.00	12	26	27	1	1
90.00	10	26	38	1	1
90.00	10	26	39	1	0
1300.00	10	26	85	1	1
375.00	10	26	87	1	1
1300.00	10	26	83	1	1
1300.00	10	26	84	1	1
150.00	10	26	88	1	1
150.00	10	26	89	1	1
150.00	10	26	90	1	1
150.00	15	26	91	1	1
375.00	12	27	26	1	1
375.00	12	28	26	1	1
375.00	12	29	26	1	1
200.00	12	30	26	1	1
200.00	12	31	26	1	0
125.00	12	32	26	1	0
188.00	80	33	83	1	1
188.00	80	34	84	1	1
188.00	80	35	85	1	1
375.00	80	36	26	1	1
375.00	80	37	86	1	1
90.00	10	38	26	1	1
90.00	10	39	26	1	0
238.00	10	40	83	1	1

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TABLE 2.5: FIELD ARTILLERY TRAFFIC DATA BASE (CONTINUED)

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
238.00	10	41	84	1	1
238.00	10	42	85	1	1
215.00	10	43	26	1	1
281.00	10	44	1	1	1
303.00	25	45	26	1	1
10.00	25	46	1	1	1
375.00	10	47	83	1	1
375.00	10	48	83	1	1
375.00	10	49	84	1	1
375.00	10	50	84	1	1
375.00	10	51	85	1	1
375.00	10	52	85	1	1
13.00	15	53	92	1	1
196.00	15	53	2	1	1
13.00	15	54	92	1	1
196.00	15	54	2	1	1
13.00	15	55	92	1	1
196.00	15	55	2	1	1
13.00	15	56	93	1	1
196.00	15	56	2	1	1
13.00	15	57	93	1	1
196.00	15	57	2	1	1
13.00	15	58	93	1	1
196.00	15	58	2	1	1
13.00	15	59	94	0	0
196.00	15	59	2	1	1
13.00	15	60	94	0	0
196.00	15	60	2	1	0
13.00	15	61	94	0	0
196.00	15	61	2	1	1
13.00	15	62	95	0	0
196.00	15	62	3	1	1
13.00	15	63	95	1	1
196.00	15	63	3	1	1
13.00	15	64	95	1	1
196.00	15	64	3	1	1
13.00	15	65	96	1	1
196.00	15	65	3	1	1
13.00	15	66	96	1	1
196.00	15	66	3	1	1
13.00	15	67	96	1	0
196.00	15	67	3	1	0
13.00	15	68	97	0	0
196.00	15	68	3	0	0
13.00	15	69	97	1	0
196.00	15	69	3	1	0
13.00	15	70	97	1	0
196.00	15	70	3	1	0
13.00	15	71	98	1	0
196.00	15	71	4	1	0
13.00	15	72	98	1	0

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TABLE 2.5: FIELD ARTILLERY TRAFFIC DATA BASE (CONTINUED)

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
196.00	15	72	4	1	0
13.00	15	73	98	1	0
196.00	15	73	4	1	0
13.00	15	74	99	1	0
196.00	15	74	4	1	0
13.00	15	75	99	1	0
196.00	15	75	4	1	0
13.00	15	76	99	0	0
196.00	15	76	4	0	0
13.00	15	77	100	1	1
196.00	15	77	4	1	1
13.00	15	78	100	1	1
196.00	15	78	4	1	1
13.00	15	79	100	1	1
196.00	15	79	4	1	1
196.00	15	80	83	1	0
196.00	15	81	84	1	0
196.00	15	82	85	1	0
2730.00	15	83	2	1	1
437.50	10	83	26	1	1
188.00	80	83	33	1	1
238.00	10	83	40	1	1
196.00	15	83	80	1	0
15.00	5	83	87	1	1
175.00	15	83	92	1	1
175.00	15	83	93	1	1
175.00	15	83	94	0	0
457.00	10	83	88	1	1
196.00	15	83	53	1	1
196.00	15	83	54	1	1
196.00	15	83	55	1	1
196.00	15	83	56	1	1
196.00	15	83	57	1	1
196.00	15	83	58	1	1
196.00	15	83	59	1	1
196.00	15	83	60	1	0
196.00	15	83	61	1	1
2730.00	15	84	3	1	1
437.50	10	84	26	1	1
188.00	80	84	34	1	1
238.00	10	84	41	1	1
196.00	15	84	81	1	0
15.00	5	84	87	1	1
175.00	15	84	95	1	1
175.00	15	84	96	1	1
175.00	15	84	97	1	0
457.00	10	84	89	1	1
196.00	15	84	62	1	1
196.00	15	84	63	1	1
196.00	15	84	64	1	1

TABLE 2.5: FIELD ARTILLERY TRAFFIC DATA BASE (CONTINUED)

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
150.00	10	90	26	1	1
457.00	10	90	85	1	1
15.00	5	90	87	1	1
175.00	15	90	110	1	1
175.00	15	90	111	1	1
175.00	15	90	112	1	1
150.00	15	91	26	1	1
175.00	15	91	113	1	1
175.00	15	91	114	1	1
175.00	15	91	115	1	1
12.00	15	92	53	1	1
12.00	15	92	54	1	1
12.00	15	92	55	1	1
135.00	10	92	40	1	1
175.00	15	92	83	1	1
12.00	15	93	56	1	1
12.00	15	93	57	1	1
12.00	15	93	58	1	1
12.00	10	93	40	1	1
175.00	15	93	83	1	1
12.00	15	94	59	0	0
12.00	15	94	60	0	0
12.00	15	94	61	0	0
135.00	10	94	40	0	0
175.00	15	94	83	0	0
12.00	15	95	62	1	1
12.00	15	95	63	1	1
12.00	15	95	64	1	1
135.00	10	95	41	1	1
175.00	15	95	84	1	1
12.00	15	96	65	1	1
12.00	15	96	66	1	1
12.00	15	96	67	1	0
135.00	10	96	41	1	1
175.00	15	96	84	1	1
12.00	15	97	68	0	0
12.00	15	97	69	1	0
12.00	15	97	70	1	0
135.00	10	97	41	1	0
175.00	15	97	84	1	0
12.00	15	98	71	1	0
12.00	15	98	72	1	0
12.00	15	98	73	1	0
135.00	10	98	42	1	0
175.00	15	98	85	1	0
12.00	15	99	74	1	0
12.00	15	99	75	1	0
12.00	15	99	76	0	0
135.00	10	99	42	1	1
175.00	15	99	85	1	1

TABLE 2.5: FIELD ARTILLERY TRAFFIC DATA BASE (CONTINUED)

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
196.00	15	84	65	1	1
196.00	15	84	66	1	1
196.00	15	84	67	1	0
196.00	15	84	68	0	0
196.00	15	84	69	1	0
196.00	15	84	70	1	0
2730.00	15	85	4	1	1
437.50	10	85	26	1	1
188.00	80	85	35	1	1
238.00	10	85	42	1	1
196.00	15	85	82	1	0
15.00	5	85	87	1	1
175.00	15	85	98	1	0
175.00	15	85	99	1	1
175.00	15	85	100	1	1
457.00	10	85	90	1	1
196.00	15	85	71	1	0
196.00	15	85	72	1	0
196.00	15	85	73	1	0
196.00	15	85	74	1	0
196.00	15	85	75	1	0
196.00	15	85	76	0	0
196.00	15	85	77	1	1
196.00	15	85	78	1	1
196.00	15	85	79	1	1
100.00	100	86	1	1	1
150.00	15	86	26	1	1
175.00	15	86	101	1	1
175.00	15	86	102	1	1
175.00	15	86	103	1	1
188.00	80	86	37	1	1
375.00	10	87	26	1	1
15.00	5	87	83	1	1
15.00	5	87	84	1	1
15.00	5	87	85	1	1
15.00	5	87	88	1	1
15.00	5	87	89	1	1
15.00	5	87	90	1	1
150.00	10	88	26	1	1
457.00	10	88	83	1	1
15.00	5	88	87	1	1
175.00	15	88	104	1	1
175.00	15	88	105	1	1
175.00	15	88	106	1	1
150.00	10	89	26	1	1
457.00	10	89	84	1	1
15.00	5	89	87	1	1
175.00	15	89	107	1	0
175.00	15	89	108	1	1
175.00	15	89	109	1	1

TABLE 2.5: FIELD ARTILLERY TRAFFIC DATA BASE (CONTINUED)

Msgs/30 hr. Scenario	Busy hr. Percentage	Trans. PRU	Dep. 1 Dest. PRU	DL Alpha	DL Bravo
12.00	15	100	77	1	1
12.00	15	100	78	1	1
12.00	15	100	79	1	1
135.00	10	100	42	1	1
175.00	15	100	85	1	1
175.00	15	101	86	1	1
175.00	15	102	86	1	1
175.00	15	103	86	1	1
175.00	15	104	88	1	1
175.00	15	105	88	1	1
175.00	15	106	88	1	1
175.00	15	107	89	1	0
175.00	15	108	89	1	1
175.00	15	109	89	1	1
175.00	15	110	90	1	1
175.00	15	111	90	1	1
175.00	15	112	90	1	1
175.00	15	113	91	1	1
175.00	15	114	91	1	1
175.00	15	115	91	1	1

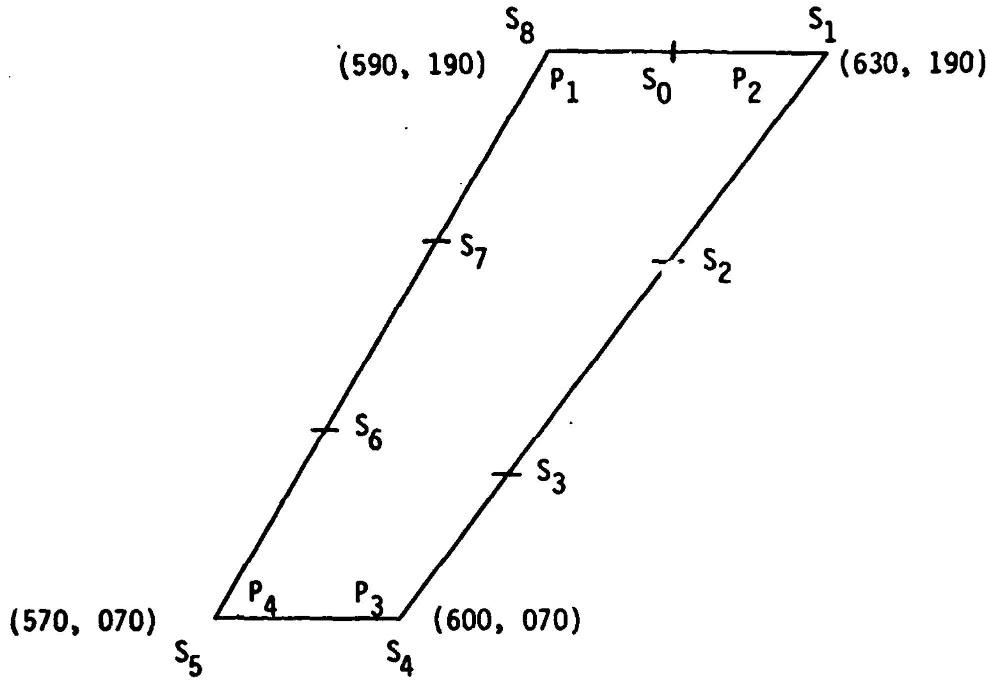

FIGURE 2.8: EXEMPLARY AERIAL TRACK ON SOUTH SECTOR ON 52D MECHANIZED DIVISION

TABLE 2.6: MOBILITY DATA BASE

Identifying Number	P1	P2	P3	P4	Velocity	Sector Parameters
79	630 460	660 460	670 340	630 340	60	10
80	640 330	670 330	640 210	620 210	60	10
81	590 190	630 190	660 070	570 070	60	10

2.3 Scenario Generator

2.3.1 Scenario Generator Module

As discussed in Section 2.1, subnetworks are functionally defined according to the following applications: Command and Control, Field Artillery, and Air Defense. The three subnetworks thus formed will be considered independent of each other, i.e., each subnet is treated as an isolated entire network by itself. Some military units, e.g., Division Main CP, may appear in multiple scenarios, and hence it is assumed such units have multiple packet radio units. During the proposed 30-hour scenario, three deployments are considered; hence, location of these PR units can be:

- Initial deployment
- Along DL ALPHA deployment
- Along DL BRAVO deployment.

Traffic can either be routed directly terminal-to-terminal or via a host where messages are temporarily stored. The total traffic volume can also be modified by scaling the volume per the 30-hour period; this is done for all needlines, but cannot be done for individual needlines. Also, the length of time to be simulated must be specified. This time depends primarily on how much time is required to achieve steady-state PR network operation. In summary, specification of the subnet, deployment, host, scale factor, and time duration defines a "scenario."

For any one scenario, the Scenario Generator module will generate the following input files for PRSIM:

- An exogenous traffic profile
- Mobility profile
- PR terminal file.

The PRSIM module will then simulate the packet radio network operations with the given PR unit locations (including mobility) and traffic as generated by the Scenario Generator module.

2.3.2 Terminal Profile

The terminal PR location file output from the Scenario Generator includes the identifying number of the packet radio unit, the coordinates of the packet radio unit for the deployment, and antenna height. This information is directly extracted from the Data Base module.

2.3.3 Traffic Profile

The traffic profile generated by the scenario generator and read by PRSIM specifies the simulated exogenous traffic by each individual message transmission time. Exogeneous traffic refers to traffic entering the network via terminals, which in turn generates internal network traffic to transport external traffic. There is no internetwork traffic explicitly considered in any scenario.

The simulated traffic file contents is sequentially arranged to their time sequence of occurrence for the specified scenario. Figure 2.9 gives a sample scenario generator output. The entries in the profile include the clock times at which the transmissions are scheduled, origination and destination PR identifying numbers, intermediate PRU's required for connectivity, and message lengths (in packets). Messages to be transmitted could be so long as to exceed one information packet length. When messages comprise several packets, these entries in TIME refer to the time the first packet is ready to be transmitted. Transmissions of subsequent packets of the same message follow automatically in sequence in a chain of events that follow transmission of a packet according to the packet radio protocol. The ninth entry in the exemplary traffic profile shows that at time 4908910 seconds, device 1 (Main Command Post) has a 3-packet message to transmit to device 2 (Brigade 1). The device number and description are associated from Data Base (Tables 2.1, 2.2, and 2.3). The source and destination PRU's are determined by the needline; the intermediate PRU's are determined by shortest path routing. A standard shortest path algorithm was implemented as part of the Scenario Generator to obtain these routes.

TIME	ROUTE								PACKETS
10	1	9	0	0	0	0	0	0	3
90410	9	1	0	0	0	0	0	0	3
264610	15	1	0	0	0	0	0	0	3
1793410	1	3	4	0	0	0	0	0	3
2344010	1	3	5	0	0	0	0	0	3
2409210	8	15	1	0	0	0	0	0	3
2964510	4	3	1	0	0	0	0	0	3
3960210	8	15	1	0	0	0	0	0	3
4908910	1	11	10	2	0	0	0	0	3
4923210	1	9	0	0	0	0	0	0	3
5201510	1	11	10	0	0	0	0	0	3
5431610	1	11	0	0	0	0	0	0	3
7075810	8	15	1	0	0	0	0	0	3
7574410	15	1	0	0	0	0	0	0	3
7667610	1	3	0	0	0	0	0	0	3
7848410	1	14	0	0	0	0	0	0	3
8008610	1	14	0	0	0	0	0	0	3
8537110	8	15	1	0	0	0	0	0	3
9696010	1	3	4	0	0	0	0	0	3
10049810	11	1	0	0	0	0	0	0	3
10206610	1	3	5	0	0	0	0	0	3
11233410	13	1	0	0	0	0	0	0	3
11448610	1	15	8	0	0	0	0	0	3
12104210	13	1	0	0	0	0	0	0	3
13184010	8	15	1	0	0	0	0	0	3
13191710	1	3	4	0	0	0	0	0	3
13300210	8	15	1	0	0	0	0	0	3
13353610	11	1	0	0	0	0	0	0	3
13759410	1	9	0	0	0	0	0	0	3
14058710	7	11	1	0	0	0	0	0	3
14909810	4	3	1	0	0	0	0	0	3
15252810	1	3	5	0	0	0	0	0	3
15665510	9	1	0	0	0	0	0	0	3
15879510	1	9	0	0	0	0	0	0	3

FIGURE 2.9: SAMPLE SCENARIO GENERATOR OUTPUT

For the C^2 and Field Artillery terminals, the time between transmissions is assumed to be random with an exponential distribution. If T is the clock time for the beginning of the simulation time, then subsequent transmissions from that PR are:

$$T + \xi_1, T + \xi_1 + \xi_2, T + \xi_1 + \xi_2 + \xi_3$$

where ξ_1, ξ_2, ξ_3 are exponential random variables generated around the mean inter-transmission time rate for that PR. T is an arbitrary time for the beginning of simulation and is identical for all devices in a particular scenario.

For ADA, the transmission times are not random but periodic. In this case, the interarrival times are assumed constant not random. Suppose D is the fixed time between messages and T is the time of the first transmission, then subsequent transmissions occur at:

$$T + D, T + 2D, T + 3D, T + 4D \ldots.$$

To compute the mean transmission time for a particular PRU, let

λ_i = number of transmissions from that particular PRU to PRU i during the busy period.

The quantity λ_i is computed by dividing the 30-hour transmission rate by 1.25 to determine the daily transmissions and then multiplying by the busy hour fraction to determine the peak hour value. Let D be the set of all destination PRU's to which a single PRU transmits. Then, the total transmission rate for that PRU to its associated destination group D is:

$$\lambda = \sum_{i \varepsilon D} \lambda_i$$

the probability of the transmission being destined for destination j in that group,

$$f_j = \frac{\lambda_j}{\lambda}$$

Then the mean intertransmission time is $1/\lambda$. For C^2 and Field Artillery, the Scenario Generator would then generate times for transmission

$$t_i = T + \sum_{k=1}^{i} \xi_k$$

as described above. For each t_i, a destination PRU would be determined randomly using the probability distribution f_j, $j \varepsilon D$.

When a message-switching host is employed, the Scenario Generator automatically redefines the needlines to accommodate the host. This is done as follows. Suppose PRU A is a host and consider a needline from PRU's B to C, where A $\neq$ B, A $\neq$ C. Then the Scenario Generator defines needlines:

- from B to A

- from A to C

with the same parameters as in the original B to C needline. Needlines for which either endpoint is a host are not modified. With the new needlines, the same methodology as described above is applied.

For ADA, the same methodology would be employed, but the time between transmissions would be fixed, i.e., the probability distribution is discrete with a single point having nonzero probability.

The following message length parameters were employed:

- 304 bits in the Field Artillery

- 5,640 bits in C2

- 76 bits ADA.

In this study, the message sizes are being taken as fixed for all information messages. However, if a message length distribution were specified, varying message lengths could have been simulated. The evaluation of the expected message length distribution indicates there is a small variance in the distribution, so the fixed length assumption was deemed valid.

A standard maximum packet length of 1,856 bits is assumed. Thus, the message of 5,640 bits would require four packets of 1,410 bits each. However, the 5640 bit message size assumes a 12-bit Hamming character code is used. With the reliable communications channel provided by the PR network, such a code is unnecessary. Assuming 8-bit characters, there are only 3,760 (8/12 x 5640) bits of information. Thus, the information bits could be accommodated in two 1,880-bit packets or three 1,254-bit packets. Three packets were assumed.

2.3.4 Mobility Traffic Profile

The motion of the Aerial Observers will be simulated by PRSIM in discrete increments. The initial locations of the Aerial Observers will be specified in the terminal location file. Then, subsequent movements will be given in the Mobility Traffic file, as shown in Figure 2.10. For each mobile PR unit, it lists PRU identifying number, the clock times (in column TIME) when it moves from one sector of the quadrangle track to the next, and the coordinates of the new sector.

There are only three Aerial Observers and they are in the Field Artillery subnetwork only during the initial deployment.

2.4 The Link Module

2.4.1 LOS Link Model

MITRE Corporation determined which devices had LOS connectivity; this information was incorporated into the data base.

2.4.2 Longley Rice Model

The alternative Link Module used to determine the communication links was based on the Longley Rice program provided by CORADCOM. The Longley Rice [6] model computes the attentuation of transmission between transmitting and receiving nodes. The model employed was the enhanced Longley Rice model that accounted for location variability using a stochastic algorithm. This algorithm is described in the Appendix. Then considering relevant geographical and environmental conditions, together with transmission R/F and

PR UNIT	TIME	NEW COORDINATES IN KMS	
79	820	X_1	Y_1
81	1,891	X_2	Y_2
80	3,160	X_3	Y_3
.	.	.	
.	.	.	
.	.	.	

FIGURE 2.10: MOBILITY FILE FROM SCENARIO GENERATOR

antenna heights parameters, a minimum threshold value of energy of reception is specified, below which a receiving PRU cannot "hear" the transmission. The Longley Rice model program computes the attenuation loss between two PR units. The calling module can then determine whether the two PR units can form a link, i.e., the attenuation losses still leave enough transmission intensity to allow reception.

CORADCOM provided the attenuation thresholds of 150 dB at the 100-Kbps data rate and 144 dB at the 400-Kbps data rate.

2.5. Packet Radio Simulation Module

2.5.1 PRSIM Capabilities

Because of the complexity of PRSIM, it is beyond the scope of this report to provide a detailed description of its capabilities. However, in this section, a high level description of PRSIM's capabilities and its input parameters is presented.

PRSIM is an event-driven simulation program. The exogenous events driving the simulation program are the message arrival events as defined in the traffic profile, generated by Scenario Generator module. PRSIM simulates both PR link protocol and end-to-end protocol (TCP). However, the opening and closing of virtual circuits are not simulated; in effect virtual circuits are assumed to be permanent.

The level of detail in PRSIM is exemplified by the basic events in the simulation; these events are

- Message arrival
- Begin reception
- End reception
- End processing of received message
- Begin transmission (radio and hardwire)
- End transmission (radio and hardwire).

Both radio and hardware transmissions are simulated. Three types of packets are modelled in the simluation:

- Information packets
- End-to-end acknowledgments
- Local repeaters-on-packets (LROP's) (optionally).

Information packets are generated by the exogenous message arrival (corresponding to the message arrival specified by the traffic profile). End-to-end (ETE) acknowledgments are generated internally in the network when an information packet is received at the destination (dependent on the TCP rules for sending such an acknowledgment). When a link acknowledgment cannot be effected by echoing, PRSIM generates an active link acknowledgment for both information and ETE acknowledgments.

LROP's packets constitute monitor and control traffic that is internal to the network. These packets are randomly generated for each PRU according to a rate and packet length as specified in the parameter input.

The capture mode simulated by PRSIM is the half amplitude mode. A packet will be received without interference if

- The channel is idle when packet reception begins.
- No packets of higher energy are subsequently received during the packet reception.

However, packets received without interference may have bit errors. The effect of detection and correction of such errors is simulated knowing the probability of a packet being received correctly or the probability of being able to correct a packet. These probabilities are an input parameter.

2.5.2 PRSIM Input

The PRSIM module will have two sets of inputs:

- Scenario Generator output information
- User information.

As discussed above, the Scenario Generator output consists of:

- The terminal location data base
- The traffic data base
- The mobility data base.

The important user supplied operational parameters for PRSIM consist of the parameters listed below:

- Length of headers in information packets (radio and end-to-end)
- Number of transmissions of an active echo in the network
- Maximum information packet length
- Fraction of high data rates capture loss due to not acquiring synchronization
- Fraction of low data rates capture loss due to not acquiring synchronization
- Number of buffers in station (based on PRU configuration)
- Number of buffers in a repeater (based on PRU configuration)
- Reactivation times of packet not acknowledged (based on TIU protocol)
- Retransmission times (based on PRU protocol)
- Number of retransmissions (based on PRU protocol)

- Number of reactivations (based on TIU protocol).

In addition, all simulations will be performed with a fixed PRU transmission power, and no internetworking (host) traffic will be explicitly modeled. The numerical values used for these parameters are specified in Section 3.

3. SIMULATION SCENARIOS

In this section, the inputs and the outputs of the simulation system are described. The inputs consist of the variables that can be controlled while the outputs consist of the statistics repeated by the simulation program.

3.1 Simulation Variables

3.1.1 Deployment/Subnetwork

The Command and Control subnetwork as deployed at the beginning of hostilities was studied in detail. The Main Command Post was recognized as an obvious bottleneck; hence initially smaller subnets around the Main Command Post was studied. The following two C^2 subnetworks were

- Support scenario depicted in Figures 3.1 and 3.2

- Brigade scenario subnetwork depicted in Figure 3.3.

The Support Scenario consists of the following eleven PRU's

- Main CP

- Division Support Command

- Maintenance BN

- Finance Company

- Supply and Transportation BN

- Adjutant General Company

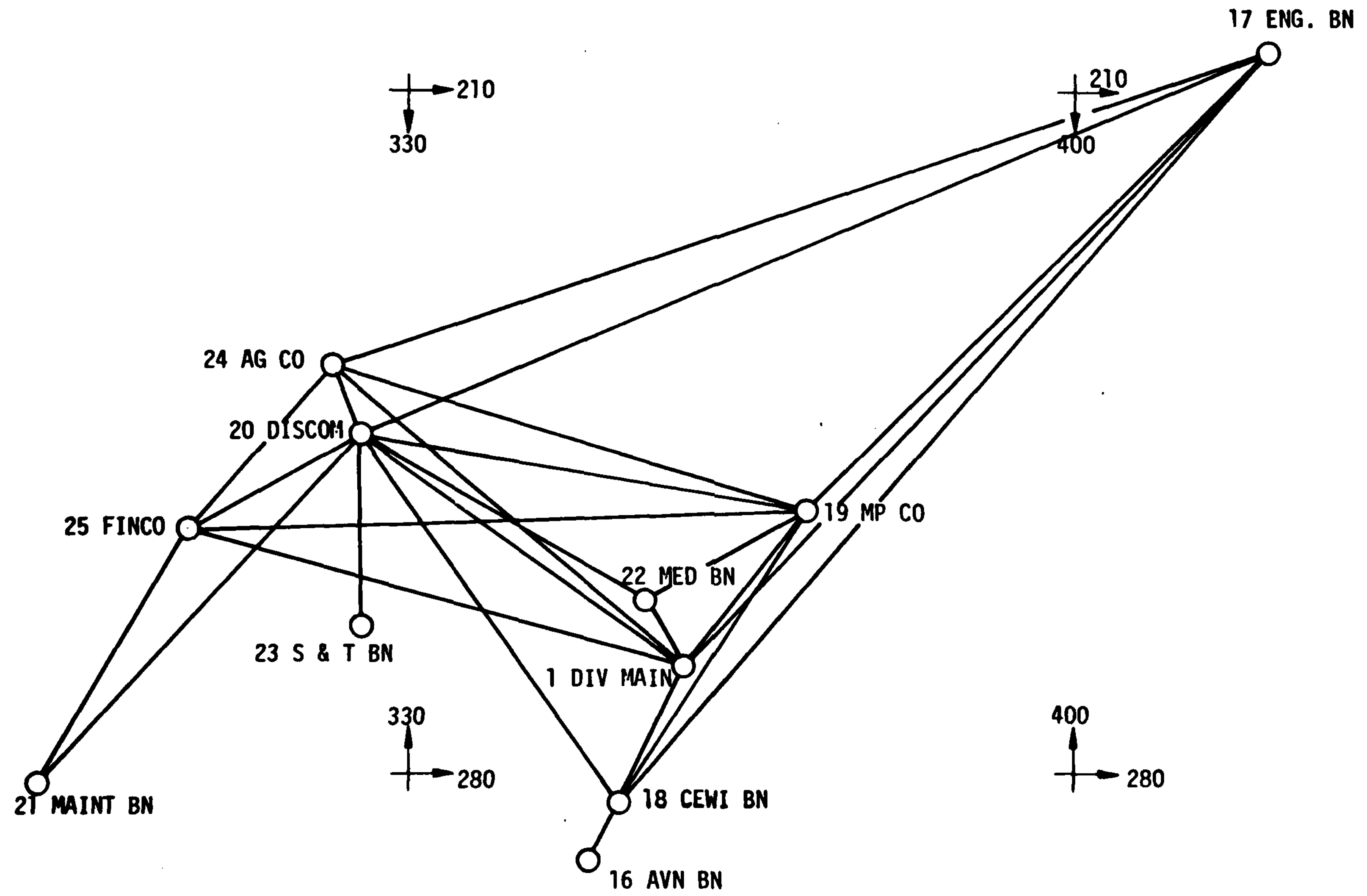

FIGURE 3.1: SUPPORT SCENARIO (LOS LINKS)

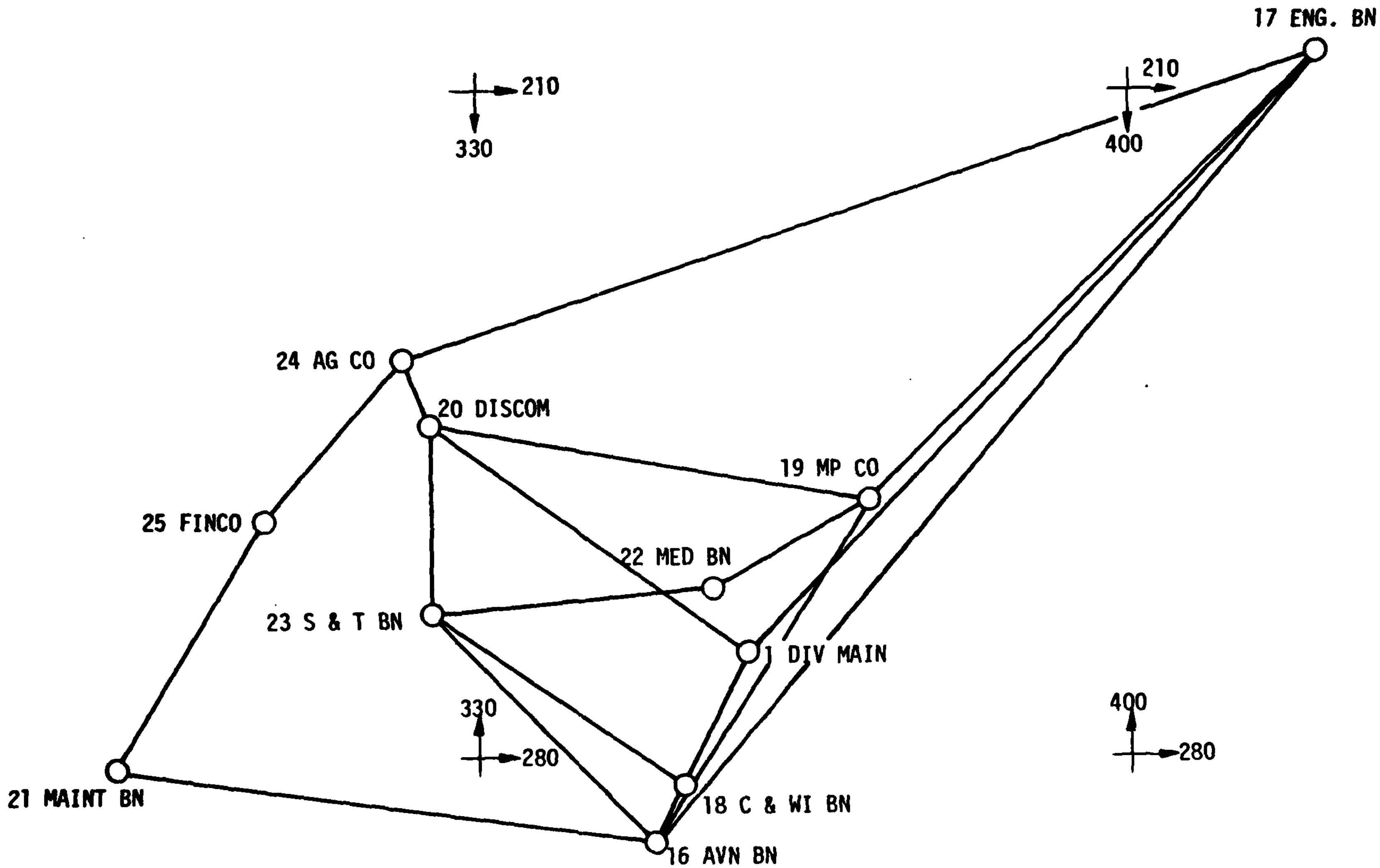

FIGURE 3.2: SUPPORT SCENARIO (RANDOM LINKS)

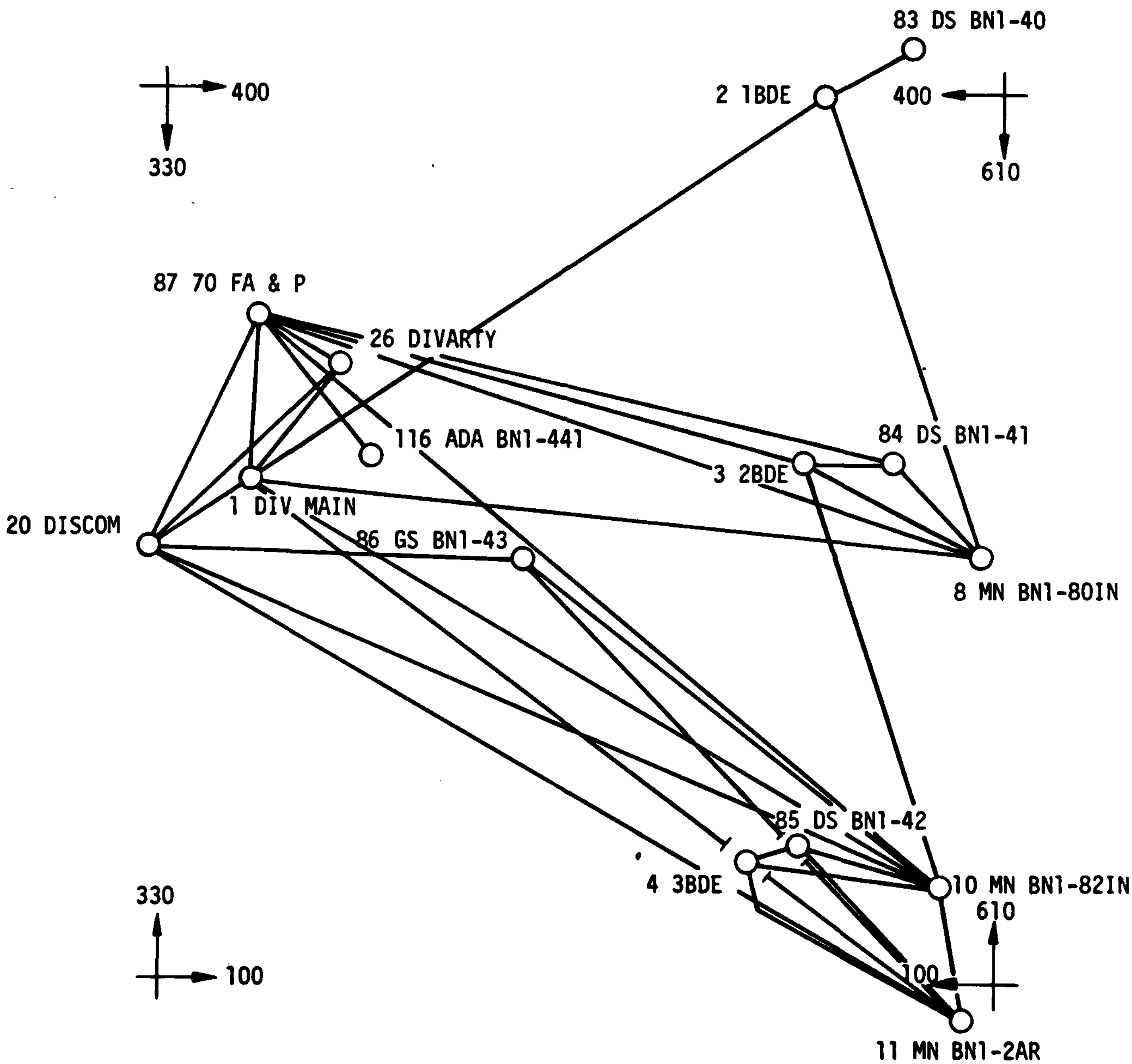

FIGURE 3.3: BRIGADE SCENARIO (LOS LINKS)

- Aviation BN
- Communications, Electronic Warfare and Intelligence BN
- Medical BN
- Military Police Co.
- Engineering BN.

These PRU's were initially chosen for simulation because of their proximity to the Main Command Post. Then the Brigades were chosen for simulation with the associated support battalions. The 15 PRU's in this simulation consisted of

- Main CP
- Division Support Command
- Field Artillery Group
- Division Artillery
- Air Defense Artillery
- 1st Brigade
- 2nd Brigade
- 3rd Brigade
- Direct Support BN 1-40
- Direct Support BN 1-41

- Direct Support BN 1-42
- General Support BN 1-43
- Maneuver BN 1-80
- Maneuver BN 1-82
- Maneuver BN 1-2AR.

These PRU's were chosen because of thier obvious functional importance.

Then nearly the entire Command and Control subnetwork was studied (only 4 PRU's were excluded).

3.1.2 Connectivity

As discussed in the Appendix, the calculation of attenuation loss is a difficult problem. For example, multipath, foliage, and terrain effects must be considered. Hence, it is very difficult to predict the network topology a priori. Two approaches have been used

- Random Longley Rice
- Line of Sight.

The random Longley Rice, which is described in the Appendix is an empirical model that computes attenuation given a measure of the terrain irregularity, h, the interdecile range.

The major drawback of this model is that it is based on averages and thus cannot take into account the detailed terrain profile. Hence, an LOS model was also used; in this model it was asumed that two PRU's could communicate with each other if and only if the two devices were in LOS of each other. Mitre Corporation performed the detailed terrain profile analysis to determine which devices were in LOS of each other. In all cases, the free space attenuation was less than the 150 dB threshold; hence, it was assumed that a link existed between all devices which were in LOS of each other.

3.1.3 Message-Switching Host Requirements

The Command and Control application could be implemented in either of two ways:

- Store and forward through a message-switching host
- Terminal to terminal.

In the store-and-forward mode through a host, the origination terminal sends its message to a host. Here the message is stored until the destination terminal requests the delivery of the message. The request for delivery is not included in the model; also messages from the host to the destination terminal informing the destination terminal a message is ready for delivery are not included in the model. Thus in this model, any message between terminals (not including the host) results in two messages, one to the host and one from the host. Thus the traffic volume is essentially doubled by the introduction of the host. Furthermore, the traffic is centralized at the host, thus additional congestion is created. The Main Command Post was selected as the host. The possibility of employing other PRU's as hosts was considered (both instead of and in addition to the Main CP), but there were no other logical choices. Since adequate performance was obtained with the Main CP as the host, this issue was not further addressed.

In the terminal-to-terminal mode traffic is transmitted directly from the origination PRU to the destination PRU. Packets of the message will be stored in the intermediate PRU's as necessary, but the entire message is not stored in an intermediate host.

3.1.4 Route Selection

As discussed in Section 2, routes are assigned a priori in the Scenario Generator using a shortest path criteria. If a message-switching host is used, shortest paths are determined between the origination/destination terminals and the host. For the terminal-to-terminal mode, shortest paths between the origination and destination terminals were determined.

For the simulations using the random connectivity model, special procedures to minimize congestion were designed; these procedures are described in Section 6. Because a smaller number of hops were required for LOS and terminal-to-terminal models, it was not necessary to develop such procedures in these cases.

3.1.5 Traffic Sensitivities

The traffic needlines, volumes, and message lengths are those supplied by MITRE as described in Section 2. The PR network offered rate is defined as

$$P = \frac{\lambda L}{R}$$

where

λ = message arrival rate

L = message length (bits)

R = data rate (bps).

Theoretically, because of spatial diversity in the terminal-to-terminal case, the network can support an offered rate of more than one. For example, two pairs of terminals that are geographically separated can simulaneously communicate, and thus, throughput is not bounded by one. However, in practical cases, the offered rate is typically a small percentage.

Initially, the message arrival rate was chosen as the nominal rate derived from the C^2 data base. Subsequently, this was scaled in the study by a factor of 2. The message length and data rate were initially held fixed.

3.1.6 PRU Parameters

The parameters in the PRU were primarily based on the experimental packet radio as defined in the Channel Access Program (CAP) 4.6. These parameters are discussed below.

3.1.6.1 Buffers

The number of buffers in the PRU's was initally chosen as 6, the number of buffers in a PRU repeater. Subsequently, the number of buffers was reduced to 3. The simulation did

not have the capability of functionally allocating buffers, i.e., allocation of certain buffers for transmision or reception or radio or 1822 use.

3.1.6.2 Link Level Protocol Retransmissions

When the packet radio transmits a packet on the radio channel, it awaits a link (hop-by-hop) acknowledgment. The PRU times out for a random period of time and will retransmit the packet if the link acknowledgment is not received. The number of times the packet will be retransmitted is a parameter.

The following parameters were used in all simulation runs:

- Expected timeout awaiting link acknowledgment: 9 milliseconds

- Number of retransmissions: 4

- Header size (including CRC and preamble): 256 bits.

3.1.7 End-to-End Level Protocol

Analogous to the link acknowledgment in the PRU, the TIU will retransmit packets if end-to-end acknowledgments are not received. For clarity of presentation, such retransmissions are referred to as reactivations; thus retransmissions occur at the link protocol level and reactivations occur at the end-to-end protocol level.

The specification of the reactiviation parameters are based on the transmission Control Program (TCP) Version 4. These parameters are:

- Number of reactivations: 10

- Random timeout awaiting receipt of end-to-end acknowledgment: 0.6 seconds

- Window size for a virtual connection: 5 packets (785 bytes)

- Header size: 150 bits.

Message lost in the PRSIM refer to those messages that were discarded after the maximum number (10) of reactivations were exceeded. Because of the communication between terminals consists of small messages interspersed relatively far apart, the window size did not affect packet transmission. The opening and closing of virtual circuits was not simulated.

3.1.8 Access Method

The non-persistent Carrier Sense Multiple Access method was used in all simulations. Because adequate performance was obtained with CSMA, other alternatives were not explored.

3.1.9 Capture

Half-amplitude capture was used in all simulations. A packet is received correctly in this capture mode if and only if:

- The receiving PRU was idle when the transmission begun.
- No packets of higher energy were subsequently received during the packet reception.
- There were no bit errors in the packet.

3.1.10 Packet Errors

Packets can be received in error if the

- Receiving PRU does not acquire or maintain synchronization upon packet reception.
- Cyclic redundancy checksum (CRC) does not match.

The probabilities of not acquiring sync or not maintaining it are typically small and were ignored in this study.

The CRC check is modeled via a channel bit error rate. The packet error rates assumed were

- 1% (initially)

- 10%.

Since these error rates are based on a 1000-bit packet, a linear scaling is performed to estimate packet error rates for other size packets. Thus smaller packets have a lower probability of being in error than larger packets.

3.1.11 PR Processing Times

Upon receipt of a packet in the radio channel, the processing delays for error correction (if applicable, BER greater than zero), protocol execution, and routing are simulated. The processing values assumed are:

- Processing delay: 6 msec

- Error correction delay: 4 msec.

3.1.12 Monitor and Control Traffic

The monitoring and control traffic in the PR network is simulated by the transmission of Local Repeater or Packets (LROP's). These packets are generated randomly with uniform distribution having the mean inter-transmission time of 60 seconds for each PRU.

Other monitor and control traffic such as Performance Data Packets, diagnostics (XRAY), route requests (to a station), or route assignment (from a station) were not modelled.

3.2 Statistics

In this section, the primary measures of system performance measured in PRSIM are described.

3.2.1 Delays

PRSIM has the capability of measuring message and packet delays on both a one-way and round-trip. The mean and standard deviation of following quantities are measured:

- First packet delay — time interval from the instant the origination TIU is ready to transmit the packet until the destination TIU receives the last bit of the packet.

- First packet round-trip packet delay — time interval from the instant the origination TIU is ready to transmit the packet until the origination TIU receives the last bit of the ETE acknowledgment for that packet.

- Round-trip message delay — time interval from the instant the origination TIU is ready to transmit the message until the origination terminal receives the last bit of the ETE acknowledgment of the last packet of the message.

- One-way packet delay — time interval from the instant packet transmission is begun by the origination TIU until the last bit of the packet is received at the destination TIU.

- One-way message delay — time interval from the instant the origination TIU transmits the first bit in the packet until the destination TIU receives last bit of the last packet of the message.

The first three quantities are recorded by the number of hops the packet must traverse from source to destination. Hence, delays per hop were computed for these statistics.

3.2.2 Offered Rate and Throughput

The offered rate, O_f, is a normalized measure of the traffic volume generated exogenous to the network; it is defined

$$O_f = \frac{n_m L_m}{tDR}$$

where

n_m = Number of messages arriving during the simulation time duration.

L_m = Message length in bits (information bits only).

DR = Radio channel data rate.

t = Time duration (in seconds) of simulation

Typically, O_f is expressed as a percentage and is less than 100%.

The throughput is a normalized measure of the packets that have been reliably delivered by the PR network; it is defined as

$$T = \frac{n_p L_m}{tDR}$$

where

n_p = Number of packets that have been delivered to the destination and for which end-to-end acknowledgments have been received.

L_m = Packet length (information bits only).
DR = Radio channel data rate.

Typically, both the offered rate and throughput are expressed as percentages and are much less than 100%. This bound on throughput is strict when packets are routed through a

host. However, for direct terminal-to-terminal routing, the throughput can exceed 100% by taking advantage of spatial diversity.

3.2.3 Buffer Utilization

Buffer utilization is the fraction of time the buffers in the PRU are occupied. The occupancy time is measured from the instant that the packet is correctly received until it is purged (due to receipt of hop-by-hop acknowledgment or maximum number of transmissions is exceeded).

Buffer utilization was not measured, but buffer overflow and maximum use were measured. Specifically, the number of times a packet had to be discarded because no buffer was available is measured and the maximum number of buffers used.

3.2.4 PRU Radio Packet Transmission/Reception Statistics

PRSIM measures the following statistics for the PRU radio interface

- Packets captured
- Packets not captured
- Packets received incorrectly (bit error)
- Packets received correctly
- Number of first transmissions
- Number of retransmissions.

These statistics provide an indication of the PRU activity.

4. SIMULATION RESULTS

This section contains the results of simulation of the:

- Brigade scenario
- Entire C^2 network scenarios
- Support scenario

as they were defined in Section 3.

In Section 4.1, the highlights of this deployment study are summarized. Results are then presented in detail in the sections characterized by the scenario and traffic profiles considered as follows:

Section 4.2.1	Brigade Scenario	Point-to-Point Routes	LOS Links
Section 4.2.2	Brigade Scenario	Host Routes	LOS Links
Section 4.3.1	Entire C^2 Scenario	Host Routes	LOS Links
Section 4.3.2	Entire C^2 Scenario	Host Routes	LOS Links
Section 4.4	Support Scenario	Host/Point-to-Point Routes	LOS and Random Links

The detailed statistical results are presented for each of the above cases in Tables 4.2 through 4.6. In the subsequent text, the referenced Run Numbers refer to the run number in Column 1 of these tables.

4.1 Summary

The simulation studies performed for the Command and Control deployment of PR networks in the Fulda Gap area indicate that the C^2 traffic load can be handled by PR nets over a wide range of operating conditions. Mean round trip (end-to-end) message delays of less than 2 seconds in the worst case can be measured. This includes the increase of traffic of 100% over the estimated volume and the reduction of PRU buffers from a nominal value of 6 to 3. These conclusions hold for both host and direct (terminal-to-terminal) routing for nearly all cases. The only exception is the host case with twice the nominal traffic load and three buffers, as discussed in Section 4.3.2. However, the performance of point-to-point routing is superior. Hence, operation of point-to-point routing could support a large traffic volume.

The introduction of dedicated repeaters in the forward area near the Bridgade PRU's reduces the number of hops certain messages must traverse in reaching their destinations. This results in a corresponding decrease in the message delays. Hence, even in cases where there is sufficient connectivity to guarantee a path exists between any pair of PRU's, network performance can be improved by the incorporation of dedicated repeaters. This is expected because the offered traffic loads are small.

The retrograde from the initial deployment to the DL BRAVO deployment results in a decrease in network connectivity. However, network performance (as measured in the Brigade Scenario) does not deteriorate and delay requirements can still be statisfied. Typically, messages had to traverse more hops, but maximum delays were less than 1.5 seconds.

In the sensitivity analysis, the size of the PRU buffer was found to be the most critical parameter. The traffic volume was determined to be extremely light, even after the traffic was scaled by a factor of 2. The low intensity of the offered traffic is illustrated in the following analysis. It is assumed in the generation of the traffic that interarrival time between messages is λ and t is the time required to transmit a message to its destination and receive an end-to-end acknolwedgment. For point-to-point routing, λ equals 797 messages/hour; while for gateway routing, λ equals 1,173 messages/hour.

Then,

$$P_t = P\text{ (no arrivals in (h, t + h))} = e^{-\lambda t}$$

for any message arrival time h. For the host requiring routing, P_t equals 0.72 for t = 1, implying that with probability greater than 0.72 a message of less than 1 second is completed before the next message arrives. The corresponding probability with gateway messages is 0.80. Other values are tabulated in Table 4.1. The general implication of this is that at any particular time there are relatively few messages in the network. This was observed in the simulations.

4.2 Simulation Results of the Brigade Scenarios

An initial set of runs were made with the brigade scenario, comprising of a subset of the C^2 units which were relatively more important. With the obvious high traffic to and from the DIV MAIN PRU node, this subset represents a high traffic subset of C^2. The brigade scenario simulations were performed in two sets. The first set used traffic profiles generated for point-to-point routing. The second set of simulation runs were with traffic profiles as generated with DIV MAIN operating as a host node for each message.

4.2.1 Simulation Results of the Brigade Scenario with Point-to-Point Routed Traffic

Initially, the simulation (Run 1) was run with traffic generated at nominal traffic load as recommended by MITRE. Twenty-five minutes of real-time network operation was simulated; this resulted in the transmission of 117 messages. Round-trip packet (first packet only) and round-trip message delay means varied from 0.156 sec and 0.338 sec for the shortest paths (one hop) to the worst case of 0.176 seconds and 0.657 sec for the longest routes (four hops), respectively. From the results of these experiments, it was concluded that the brigade scenario subnetwork could more than adequately handle the present traffic load.

To test the subnet more severely, a two-step approach was then taken. As a first step (Run 2), the traffic input rate to the network was scaled up 100%. As a second set (Run 3), with this increased traffic, the number of buffers available to each PRU was halved from 6 to 3. With the traffic doubled, there was relatively little deterioration in performance; the delays for the longer routes increased comparatively more than for shorter routes. This increased delay is typically reflected in the increased round-trip message delay mean of 0.413 sec, up 9.8%.

The subsequent reduction in buffer capacity introduced caused more significant changes in delay. One-way message delay was now 0.489 seconds (up 18%), and on a per hop

TABLE 4.1: PROBABILITIES THAT MESSAGE SERVICE COMPLETE BEFORE NEXT ARRIVAL

Message Service Time (Sec)	Probability Message is Completed Before Next Arrival	
	Host	Point-to-Point
0.5	.85	.89
1.0	.72	.80
2.0	.52	.64

TABLE 4.2: SCENARIO: BRIGADE, ROUTING: POINT-TO-POINT, LINKS: LOS

Simulation Number	Scale Factor	Comments	Number Of Hops	Packet Delay (Sec) First One Way	Packet Delay (Sec) Packet Round Trip	Packet Delay (Sec) All Packet	Message Delay (Sec) One Way	Message Delay (Sec) Round Trip	Traffic Input %	Traffic Lost %
1.0	1.0	6 Buffers 1.33 Hops (Avg)	1 2 3	0.080 0.129 0.176 (0.075 Hop)	0.157 0.283 0.441 (0.153 Hop)	— 0.150 —	— 0.376 —	0.338 0.520 0.657 (0.313 Hop)	— 0.30 —	— 0.00 —
2.0	2.0	6 Buffers 1.38 Hops (Avg)	1 2 3	0.080 0.123 0.182 (0.075 Hop)	0.156 0.306 0.478 (0.156 Hop)	— 0.138 —	— 0.413 —	0.336 0.544 0.756 (0.318 Hop)	— 0.67 —	— 0.00 —
3.0	2.0	3 Buffers 1.38 Hops (Avg)	1 2 3	0.079 0.138 0.177 (0.075 Hop)	0.152 0.317 0.454 (0.153 Hop)	— 0.163 —	— 0.489 —	0.372 0.712 1.019 (0.366 Hop)	— 0.67 —	— — 0.00
4.0	2.0	Tnl Intex Packet Transmission Time Doubled 3 Buffers 1.33 Hops (Avg)	1 2 3	0.081 0.127 0.183 (0.076 Hop)	0.147 0.257 0.374 (0.142 Hop)	— 0.113 —	— 0.501 —	0.509 0.724 0.847 (0.465 Hop)	— 0.67 —	— — 0.00
5.0	2.0	Brigade Point-to-Point LOS, DL BRAVO 1.87 Hops (Avg)	1 2 3 4	0.084 0.133 0.141 0.170 (0.074 Hop)	0.167 0.305 0.312 0.406 (0.158 Hop)	— 0.138 —	— 0.351 —	0.346 0.516 0.665 0.859 (0.300 Hop)	— 0.67 —	— 0.00 —

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basis, measured round-trip message delays were up an average of 15%. There was no indication of messages with longer routes being especially delayed. The general increase in delay times could be associated with the frequent unavailability of buffers, causing the relatively higher ratios of retransmission.

In an attempt to control excessive copies of packets in the subsequent run (Run 4), with traffic and buffer capacity held constant, a flow control procedure was implemented. This was done by doubling the time between terminal transmissions. This improved delays generally on a per hop basis. Also, a general reduction in buffer congestion was observed. However, the introduced delay in sending out the information packets caused increased in one-way and round-trip message delays of 2.5% and 27%, respectively.

The Brigade scenario was next simulated (Run 5) with the same increased point-to-point traffic and six buffers but in the DL BRAVO deployment. The DL BRAVO deployment has a new set of LOS links. With the LOS link connectivity, the needlines of the scenario are now satisfied by routes varying from a minimum of one hop to a maximum of four hops. The mean number of hops goes up to 1.87 in the DL BRAVO deployment as compared to 1.33 for a similar run in the initial deployment.

The overall round-trip packet and message delays, however, do not change significantly. Thus, the round-trip packet delay per hop is 0.158 seconds which is 1.3% higher and round-trip message delay per hop is 0.300 seconds which is only 5.6% less than their corresponding values in the initial deployment. Even with its greater mean number of hops in the DL BRAVO deployment, the overall delay means are comparable to the initial deployment values and can be further illustrated by looking at one-way delays. It is observed that in the worst case (i.e., longest routes) for initial deployment one-way packet delay is 0.182 sec. The one-way delay for the longest routes in the DL BRAVO deployment is only 0.170 sec, an improvement of 7%. In fact, overall one-way message delay is also 0.351 sec which is an improvement of 15%. This change in delay is likely caused by the change in network topology from the initial deployment to DL BRAVO.

From the above, we conclude:

- Traffic loads are significantly lower than the subnet capacity. Thus, significant changes are not noticeable even by doubling traffic.

- At the operating traffic loads, while six buffers per PRU may be slightly more than optimally required, at traffic loads of this order, it is a sensitive factor.

- A buffer reduction will cause greater message delays. However, the congestion introduced does not catastrophically deteriorate network performance.

- Even with a significant decrease in network connectivity in DL BRAVO, network performance is still adequate.

4.2.2 Simulation Results of Brigade Scenario with Host Routed Traffic

As explained in Section 3, other traffic generating parameters being the same, a traffic profile with routing through a host node is approximately twice the number of messages for a similar but point-to-point routed traffic. With DIV MAIN operating as centrally located host, the shortest paths for needlines are shorter than for point-to-point routes. However, owing to the distribution of number of hops per needline, the overall mean number of hops/message remains essentially the same around 1.36. Furthermore, the effect of buffer capacities would be expected to be more critical at the host and possibly other close by heavily loaded nodes.

As in the point-to-point case, for purposes of comparison, a base run (Run 6) was made with the nominal traffic and six buffers per PRU. This comprised of 166 messages over the 25 minutes of real-time simulated. Subsequently, in a two-step process of introducing congestion, the buffer capacity was halved and then traffic was increased by 100%.

With initial traffic and six buffers (Run 6), round-trip packet and message delay means varied from 0.165 sec and 0.341 sec for the shortest routes to 0.296 sec and 0.522 sec, respectively, for the longest routes. These delays are comparable to their values in the comparable point-to-point run. Although there is increased congestion at the host, overall delays are comparable because the load is relatively light.

Buffer reduction (Run 7) caused a start in buffer overflows and higher incidence of retransmissions. Generally, these caused higher delays (e.g., round-trip message delay mean up 6% to 0.317 sec), but with traffic still being relatively light the effect was not significant. In the second step (Run 8), introduction of twice the traffic, significant changes were seen.

- Round-trip message delay up 32% to 0.418 sec

- One-way mesage delay up 65% to 0.539 sec

TABLE 4.3: SCENARIO: BRIGADE, ROUTING: HOST, LINKS: LOS

Simulation Number	Scale Factor	Comments	Number Of Hops	Packet Delay (Sec) First One Way	Packet Delay (Sec) Packet Round Trip	Packet Delay (Sec) All Packet	Message Delay (Sec) One Way	Message Delay (Sec) Round Trip	Traffic Input %	Traffic Lost %
9.0	1.0	With LROP's 6 Buffers 1.39 Hops (Avg)	1 2	0.084 0.124 (0.075 Hop)	0.165 0.296 (0.158 Hop)	0.100 —	0.341 —	0.341 0.522 (0.310 Hop)	— 0.43	— 0.00
8.0	2.0	3 Buffers 1.35 Hops (Avg)	1 2	0.083 0.142 (0.079 Hop)	0.186 0.357 (0.185 Hop)	0.100 —	0.539 —	0.441 0.751 (0.418 Hop)	0.92 —	0.00 —
7.0	1.0	3 Buffers 1.39 Hops (Avg)	1 2	0.078 0.127 (0.073 Hop)	0.158 0.291 (0.153 Hop)	0.097 —	0.326 —	0.342 0.537 (0.317 Hop)	0.43 —	0.02
6.0	1.0	6 Buffers 1.39 Hops (Avg)	1 2	0.080 0.124 (0.073 Hop)	0.154 0.286 (0.150 Hop)	0.075 —	0.338 —	0.332 0.497 (0.300 Hop)	0.43 —	0.00 —
10.0	2.0	No Error Processing Time 1.35 Hops (Avg)	1 2	0.088 0.145 (0.183 Hop)	0.181 0.239 (0.161 Hop)	0.088 —	0.526 —	0.397 0.525 (0.397 Hop)	0.92 —	0.00 —
11.0	2.0	With LROP's Prob. of Correction 0.90 3 Buffers 1.35 Hops (Avg)	1 2	0.141 0.175 (0.122 Hop)	0.284 0.506 (0.273 Hop)	0.113 —	0.677 —	0.922 0.31 (0.829 Hop)	0.92 —	0.00 —
12.0	2.0	Brigade, DL BRAVO Gateway, LOS 6 Buffers 1.66 Hops (Avg)	1 2 3 4	0.086 0.126 0.127 0.113 (0.071 Hop)	0.199 0.286 0.328 0.223 (0.159 Hop)	— — 0.088 —	— — 0.563 —	0.447 0.664 0.780 0.704 (0.376 Hop)	— — 0.92 —	— — — 0.00

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- Round-trip packet delay up 21% to 0.185 sec/hop.

In observation similar to the point-to-point case, it was observed that a significant number of buffer overflows had increased with an appreciably higher ratio of transmissions. However, delays were still of a reasonable magnitude, and the network was capable of taking the load.

In order to increase buffer availability with the same traffic and network conditions, the packet error processing time was eliminated (Run 10). Thus, packets received in error would not occupy buffer space awaiting further copies to be used in their error correction. This resulted in a 5% improved round-trip message delay time. This was effective in increasing buffer availability because many packets required in a PRN are extraneous; also, with a message error rate of .01, multiple copies of a packet are typically not needed for error correction.

The effect of introducing monitor and control traffic (LROP) was also investigated. Initially, a simulation (Run 9) was performed with the nominal traffic value and buffer capacity, but with LROP packets being transmitted. The resulting delay statistics were not markedly different from those measured in the ase run. In fact, all variations were within 4%.

Then, a simulation (Run 11) was made with the scaled up traffic, three buffers and LROP's. In the run, the probability of receiving a 1,000 bit packet correctly was reduced from the value of 0.99 to 0.90. As would be expected, compared to the comparable run with probability 0.99, delays now were greater and had significantly higher standard deviations. This wide disparity is due to the now greater number of packets which are received incorrectly, and thereby, have to wait for retransmissions (copies) to get through. In fact, a large number of LROP's can be received incorrectly and tie up buffers. With the increase in the number of packets received incorrectly and limited buffer capacity, the number of overflows were about three times more, and PRU's had significantly higher ratios of retransmissions to first transmissions. In numerical terms, the highlights of changes (computed relative to simply reducing buffer capacity and increasing traffic) were:

- Round-trip message delay mean/hop up 100% to 0.829 sec

- Round-trip packet delay mean/hop up 48% to 0.273 sec

- Total round-trip delay mean was 1.31 sec in the longest routes (2 hops) and total round-trip packet delay times for these routes werw 0.506 sec.

Since the introduction of LROP's in previous experiments had only marginal effect, we would conclude the increase in packet error rate is much more significant than the introduction of LROP traffic.

Finally, the brigade scenario was simulated (Run 12) with gateway traffic up 100% and employing 6 buffers per PRU in the DL BRAVO deployment. In the DL BRAVO deployment, the new LOS links provide less connectivity than in the initial deployment. Thus, to route host traffic, the routes vary now from one to four hops long as against only one or two hop routes in the initial deployment. This translates to an increased mean number of hops to 1.66 in this deployment as compared to 1.35 for the initial deployment.

Generally comparing results of the run, it is seen that for the longest routes (4 hop), one-way delays are comparable and sometimes even better than the corresponding delays for the longest routes (2 hop) in the initial deployment. However, congestion at and around the gateway seems to cause increased round-trip message delays, the worst case being 0.780 sec.

It is seen that delays for 3-hop routes are greater than the corresponding delays for 4-hop routes. This further implies that in this scenario route lengths do not completely influence delays. Rather, connectivity at and around the host has a more important impact.

From the above results, we conclude:

- At nominal traffic loads, host traffic does not introduce sufficient congestion to cause appreciably increased delays over the point-to-point routed case.

- With host traffic, a reduction of buffer capacity has a more pronounced effect on delays than in point-to-point routed traffic. It is possible to isolate certain PRU nodes in the entire C^2 net that may show their relative locations, be particularly susceptible to reduced buffers.

- Elimination of packet error processing time in PRU buffers enables smoother and faster traffic flow.

- The effect of introducing LROP's as additional traffic at the initial level of traffic does not affect network characteristics.

- The environment (quantified by the assumed message error rate) has a very significant effect on delays.

- It appears due to a high connectivity of the PRU's in this scenario, routes are reasonably short. This allows grood traffic flow and helps keep the subnet from degenerating under more severe conditions of buffer availability, increased traffic and lower probabilities of receiving packets correctly.

- Even with a significant decrease in connectivity in DL BRAVO, network performance does not deteriorate.

4.3 Simulation of 32 PRU's Net Scenario

In this study, the performance of a PR net with 32 PRU's was evaluated. In this case, only four PRU's (each with a low traffic generation rate) were excluded from the scenario. The excluded PRU's were:

- Cavalry Squadron

- Engineering Battalion

- Maintenance Battalion

- Finance Company.

4.3.1 Simulation Results of C^2 Scenario with Point-to-Point Traffic (32 PRU's)

As in previous sets of runs, a base run (Run 13) with the nominal peak rate of traffic and six buffers were made comprising of 289 messages during the 25 minutes of real-time simulated. Because of a greater spread in location among the C^2 PRU's compared to the Brigade scenario, point-to-point routes for C^2 scenarios needlines vary from one to four hops. For example, the communication of Maneuver Battalions with the Main Command Post typically requires a large number of hops. The mean number of hops is roughly 1.72 as compared to 1.35 for the Brigade scenario. Round-trip packet and message delay means in

TABLE 4.4: SCENARIO: ENTIRE NET, CONNECTIVITY: POINT-TO-POINT, LINKS: LOS

Simulation Number	Scale Factor	Comments	Number Of Hops	Packet Delay (Sec) First One Way	Packet Delay (Sec) Packet Round Trip	Packet Delay (Sec) All Packet	Message Delay (Sec) One Way	Message Delay (Sec) Round Trip	Traffic Input %	Traffic Lost %
13.0	1.0	6 Buffers 1.71 Hops (Avg)	1	0.081	0.159	—	—	0.347	—	—
			2	0.192	0.329	—	—	0.603	0.66	—
			3	0.233	0.553	0.200	0.526	0.819	—	0.00
			4	0.238	0.547	—	—	0.985	—	—
				(0.074 Hop)	(0.161 Hop)			(0.318 Hop)		
14.0	2.0	6 Buffers 1.64 Hops (Avg)	1	0.086	0.168	—	—	0.354	—	—
			2	0.134	0.320	—	—	0.575	—	0.00
			3	0.194	0.463	0.163	0.589	0.802	1.12	—
			4	0.237	0.584	—	—	1.103	—	—
				(0.077 Hop)	(0.163 Hop)			(0.322 Hop)		
15.0	1.0	3 Buffers 1.74 Hops (Avg)	1	0.084	0.179	—	—	0.430	—	—
			2	0.138	0.337	—	—	0.778	—	—
			3	0.229	0.513	0.225	0.613	1.014	0.66	—
			4	0.238	0.582	—	—	1.376	—	0.00
				(0.077 Hop)	(0.172 Hop)			(0.403 Hop)		
16.0	2.0	With LROP as Extra Traffic 3 Buffers 1.69 Hops (Avg)	1	0.090	0.184	—	—	0.563	—	—
			2	0.149	0.439	—	—	1.001	—	—
			3	0.208	0.643	0.125	0.827	1.453	0.97	—
			4	0.266	0.845	—	—	1.863	—	0.00
				(0.071 Hop)	(0.198 Hop)			(0.531 Hop)		
17.0	1.0	With LROP's 6 Buffers 1.74 Hops (Avg)	1	0.080	0.159	—	—	0.338	—	—
			2	0.134	0.316	—	—	0.558	—	—
			3	0.206	0.506	0.238	0.539	0.854	0.66	—
			4	0.240	0.532	—	—	0.904	—	0.00
				(0.073 Hop)	(0.157 Hop)			(0.305 Hop)		
18.0	2.0	With LROP's 6 Buffers 1.69 Hops (Avg)	1	0.082	0.161	—	—	0.345	—	—
			2	0.142	0.332	—	—	0.560	—	—
			3	0.190	0.485	0.100	0.526	0.898	0.97	—
			4	0.236	0.639	—	—	1.475	—	0.00
				(0.075 Hop)	(0.162 Hop)			(0.316 Hop)		

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this scenario were 0.159 sec and 0.347 sec for one-hop routes to 0.238 sec and 0.985 sec, respectively for the longest routes (4 hops). Hence, all one-way and round-trip delays (actual) were appreciably greater than for the similar runs with brigade scenario.

Subsequently, runs were made by:

- Increasing traffic 100% but keeping buffer capacity at 6
- Decreasing buffer capacity to 3 but keeping initial traffic constant
- Both increasing traffic 100% and decreasing buffer capacity to 3.

The effect of increased traffic (Run 14) was only marginally greater in heavier traffic case. For example, the one-way message delay increased from 0.526 sec to only 0.589 when the traffic volume was doubled. The round-trip message delay increased from 0.985 sec to 1.103 sec. Furthermore, on per hop basis round-trip packet and message delays/hop were 0.163 sec (up 1.2%) and 0.322 sec (up 1.3%), respectively.

The effects of a buffer reduction (with traffic scale factor 1.0) were more pronounced (Run 15) than those of increased traffic. Thus, round-trip packet and message delay means/hop were 0.172 sec (up 7%) and 0.403 sec (up 27%), respectively. It was observed that delays for the relatively longer routes were especially higher. This is due to buffer congestion. Thus, the longer a packet route is, the more times it has to compete for buffer space in PRU's in route. The run with buffer size 3 and nominal traffic yielded round-trip packet and message delays of 0.582 sec and 1.376 sec for the longest routes. These figures are increased of 6% and 40% over their values in the base test run.

In the next run (Run 16), the effects of reduced buffer capacity and increased traffic were combined. Additionally, LROP packets were introduced with regular traffic. The combined effect produced delays of almost 2 sec which appears close to the assumed maximum acceptable value of round-trip message delay. In the best case, i.e., for the 1 hop route round-trip packet and message delays, were 0.184 sec and 0.563 sec, respectively. In the worst case of 4-hop routes, these values respectively were 0.345 sec and 1.863 sec.

A rather large number of buffer overflows occurred, and the general level of retransmissions needed was high. It was observed that standard deviations for longer route statistics were proportionately high. This would indicate due to the lack of buffer space a relatively large number of these meassages were reactivated in the TIU after not receiving

an ETE ACK.

In two separate runs, LROP traffic was considered with first initial level traffic (Run 17) and their doubled traffic (Run 18). In both cases, the effects of LROP's were not of significance. Statistics reported in each of these runs were essentially the same as the respective runs without the LROP's.

From the above results, we conclude:

- Traffic for C^2 scenario is light and an escalation of traffic by 100% does not produce significant variations in performance.

- Reduction of buffer capacity significantly deteriorates performance. For example, buffer reduction causes relatively significant delays for 3 hop and longer routes by as much as 40%.

- Under the dual effect of reduced buffers and increased traffic, C^2 net scenario produces delays that are around 2 sec for messages traveling 4-hop routes. Traffic level is not as serious a problem as unavailability of buffers.

- With six buffers, LROP traffic did not cause any deterioration in performance.

4.3.2 Simulation Results of C^2 Net Scenario with Host Traffic

In this scenario, DIV MAIN again operates as a host for all traffic. The shortest path routes vary from 1 to 4 hop routes. The mean number of hops/message of 1.59, however, is less than 1.74 as in point-to-point routing. As explained in Section 3, host traffic for a scenario is approximately twice the number of messages for the same conditions with point-to-point routing.

As in the previous studies, a base ru.. (Run 19) was made with the recommended peak rate of traffic and six buffers. Round-trip packet and message delays for this case were 0.162 sec and 0.355 sec for 1-hop routes compared to 0.869 sec and 1.266 sec (respectively) for the 4-hop routes. For the 1-hop routes, these delays are essentially equal to those determined in the point-to-point case, but for the 4-hop routes, there are significant increases. For example, in the host case, the 4-hop round-trip packets (.869 sec) and round-trip message (1.266 sec) are 59% and 29% greater than the delays experienced in the point-

TABLE 4.5; ENTIRE SCENARIO: ENTIRE NET, CONNECTIVITY: HOST, LINKS: LOS

Simulation Number	Scale Factor	Comments	Number Of Hops	Packet Delay (Sec) First One Way	Packet Delay (Sec) Packet Round Trip	Packet Delay (Sec) All Packet	Message Delay (Sec) One Way	Message Delay (Sec) Round Trip	Traffic Input %	Traffic Lost %
21.0	1.0	3 Buffers 1.59 Hops (Avg)	1	0.097	0.208	—	—	0.464	—	—
			2	0.161	0.393	—	—	0.821	0.98	—
			3	0.205	0.527	0.125	0.601	1.078	—	0.00
			4	0.258	0.664	—	—	1.509	—	—
				(0.088 Hop)	(0.200 Hop)			(0.436 Hop)		
20.0	1.0	With LROP's 6 Buffers 1.59 Hops (Avg)	1	0.087	0.169	—	—	0.365	—	—
			2	0.149	0.356	—	—	0.605	0.98	—
			3	0.195	0.497	0.100	0.401	0.995	—	0.00
			4	0.251	0.633	—	—	1.064	—	—
				(0.080 Hop)	(0.172 Hop)			(0.337 Hop)		
19.0	1.0	6 Buffers 1.59 Hops (Avg)	1	0.084	0.162	—	---	0.355	—	—
			2	0.157	0.357	0.150	---	0.614	0.98	0.00
			3	0.177	0.499	—	—	0.989	—	—
			4	0.269	0.869	—	—	1.266	—	—
				(0.080 Hop)	(0.171 Hop)			(0.335 Hop)		
23.0	2.0	Entire Net Gateway LOS With 2 Relays 6 Buffers 1.50 Hops (Avg)	1	0.089	0.175	—	—	0.370	—	0.00
			2	0.149	0.346	0.088	0.376	0.614	2.02	—
			3	0.211	0.504	—	—	0.872	—	—
				(0.082 Hop)	(0.174 Hop)			(0.340 Hop)		
22.0	2.0	6 Buffers 1.60 Hops (Avg)	1	0.090	0.179	—	—	0.381	—	—
			2	0.152	0.368	—	—	0.606	—	—
			3	0.223	0.547	0.138	0.426	0.954	2.12	—
			4	0.220	0.586	—	—	1.139	—	0.00
				(0.083 Hop)	(0.179 Hop)			(0.345 Hop)		

DELAYS IN PARENTHESES ARE PER HOP

to-point case. This is caused by the congestion around the host where PRU's (83 and 24) experience a large number of retransmissions. Note the standard deviation in the host case for messages with 4 hops with 0.850 sec is high; this is likely caused by messages not being successfully transmitted on the first attempt and hence requiring reactivation in the TIU.

The next simulation (Run 20) made was with the LROP packets as additional traffic to the nominal host traffic employed. As had been experienced in the past with LROP's, at this level of traffic, they introduce no effect on delay statistics. For example, delays per hop were less than 1% different. The existing congestion around the host is once again highlighted by the increased number of retransmissions necessitated by the LROP's.

In a subsequent simulation (Run 21), buffer capacity was reduced to 3 and the initial traffic was used with no LROP's. As expected, buffer overflows frequently occurred with the host having the most of them. There were more retransmissions as evidenced by the retransmission ratios of device 12, increasing from 1.40 to 1.58. Also, the buffer overflows caused appreciably higher delays. This round-trip packet and message delay per hop was 0.200 sec (up 17%) and 0.436 sec (up 30%), respectively.

Next, the entire C^2 network was simulated (Run 22) with the host traffic scaled up by a factor of 2 and using 6 buffers. The results were essentially as expected, compared to a similar run, but with initial level of traffic, the changes were consistent with observations made from other runs. Round-trip packet and message delays per hop did increase to 0.179 sec (up 5%) and 0.345 sec (up 3%), respectively. As mentioned with the point-to-point set of runs for C^2 net, it is similarly observed here also that the increase in delays with greater traffic is modest indicating a light traffic load.

Finally, the scenario was simulated (Run 23) with the introduction of two relays in locations and LOS links as follows:

x Relay 1: 490 394

Relay 2: 500 210

The introduction of relays brought the mean number of hops per message down to 1.50 from 1.60 in the equivalent run without relays. Round-trip packet and message delays per hop also improved to 0.174 sec (3% decrease) and 0.340 sec (2% decrease). These improvements in overall delays considering all messages of different routes seems small. But the introduction of relays with LOS links to the host is estimated by looking at

the improvement they bring to the longer route delays. Thus, for the longest route, the round-trip packet and message delays per hop are 0.504 sec (16% improvement) and 0.872 sec (23% improvement), respectively.

Subsequent experiments in which buffer capacity was reduced to 3 indicated severe congestion around the host. Throughput deteriorated to zero indicating that the network could not operate with only 3 buffers at the gateway.

From the above results, we conclude:

- The base run statistics compared to the similar run employing point-to-point routing indcates that round-trip delays for 3- or 4-hop routes may be reduced by employing repeaters to improve performance.

- At the traffic rates considered for PRU's comprising the gateway and ones with LOS links directly to it, buffer capacity of 6 seems optimal. Any further delay would result in comparably higher delays especially for longer routes messages.

- Simultaneous increase in traffic by a scale factor of 2 and reduction of buffer capacity to 3 causes a catastrophic deterioration in performance.

4.4 Simulation Results of Support Scenario with either Host/Point-to-Point Routing

Also, a subset of PRU geographically positioned around the Main Command Post was evaluated; this subset is referred to as the Support scenario. Three runs were made, all with the same volume of traffic as recommended (nominal traffic loads). The variation of the runs was in the routing employed and link criteria. LOS links were used for one run employing a host (Run 25) and the other point-to-point (Run 26) routing traffic. In a third run (Run 27), a randomly generated (using the Longley Rice model) set of links was used to route traffic through host DIV MAIN.

In this scenario, the performance of the three cases is very similar. This is illustrated by the following mean round-trip delays:

- Host/LOS .328 sec/hop

TABLE 4.6: SCENARIO: SUPPORT, CONNECTIVITY: HOST/POINT-TO-POINT, LINKS: LOS/RANDOM

Simulation Number	Scale Factor	Comments	Number Of Hops	Packet Delay (Sec) First One Way	Packet Delay (Sec) Packet Round Trip	Packet Delay (Sec) All Packet	Message Delay (Sec) One Way	Message Delay (Sec) Round Trip	Traffic Input %	Traffic Lost %
		Gateway								
		LOS Links	1	0.082	0.158	—	0.376	0.348	0.29	0.00
25.0	1.0	6 Buffers	2	0.123	0.313	0.075	—	0.479	—	—
		1.25 Hops (Avg)		(0.077 Hop)	(0.157 Hop)			(0.328 Hop)		
		Point-to-Point								
		LOS Links	1	0.085	0.158	0.100	0.313	0.342	0.19	—
26.0	1.0	6 Buffers	2	0.154	0.301	—	—	0.520	—	0.00
		1.12 Hops (Avg)		(0.084 Hop)	(0.157 Hop)			(0.332 Hop)		
		Gateway Random								
		Links	1	0.082	0.162	—	—	0.349	—	—
27.0		6 Buffers	2	0.125	0.277	0.088	0.313	0.486	—	0.02
		1.49 Hops (Avg)	3	0.164	0.444	—	—	0.657	0.29	—
			4	0.206	0.512	—	—	0.666	—	—
				(0.072 Hop)	(0.149 Hop)			(0.316 Hop)		

DELAYS IN PARENTHESES ARE PER HOP

- Point-to-point .332 sec/hop

- Host/Random .316 sec/hop

The delays above are given on a per hop basis, i.e., the measured round-trip delay is divided by the number of hops and averaged over all samples. Note that in the LOS cases, the routes have a maximum number of two hops while in the random cases, there are some routes with three and four hops. Thus, the longest round-trip delays are experienced in the random case with routes having four hops. However, even in this case, the round-trip message delay is less than .700 seconds.

On a comparison of the two host traffic runs for this scenario, it is observed that the connectivity using LOS links yields a general improvement as compared to random set of links determining connectivity. Thus, the round-trip packet and message delays per hop reduce 5% (to 0.149 sec) and 4% (to 0.316 sec), respectively, but these changes are relatively small and insignificant. However, it is pointed out in the preceding paragraph, the random link connectivity results in an increased mean number of hops per route. This would normally be expected to produce an increase in overall mean delays which is not reflected in the results. It is inferred that there is a general congestion around the host. This is not catastrophic at these loads of traffic. Nevertheless, the use of more varied routes and different PRU's to reach the host reduces the delay.

Comparing the two runs using LOS connectivity essentially is a comparison of network performance with:

- roughly a double rate of traffic (actually closer to 50% since messages to/from the host require only one transmission in both cases)

- centralized concentration of traffic at the host node.

The delay statistics of the two runs generally differ by a few milliseconds only. It is observed, as would be expected, heavier congestion around the host and higher ratios of retransmission needed by PRU's serving as access to the host. However, the effects of this as seen are minor at these loads.

From the above results, it is concluded:

- The support scenario connectivity allows for satisfying its needline requirements with of the same order as the brigade scenario.

- Performance with LOS and random links is comparable.

- A certain small improvement in delay times may be effected by distributed traffic through different PRU's to reach the host node. This is especially so for longer routes. However, the changes are minor.

5. THROUGHPUT ANALYSIS FOR TANDEM REPEATER NETWORK

5.1 Summary and Introduction

In this section the maximum throughput is computed for a tandem network of N repeaters depicted in Figure 5.1. Both Carrier Sense Multiple Access and ALOHA Multiple Access techniques were employed. In this network, repeater i can communicate with only repeaters $i - 1$ and $i + 1$. Each repeater (2,...,N-1) wishes to send messages at a rate S in each direction, while repeaters 1 and N transmit in one direction only. Statistical dependence of adjacent message streams is ignored and independent message streams originating at each node (terminal or repeater) are assumed; note that there are two such streams at each repeater except repeaters 1 and N. S is measured in average number of messages in the time taken to transmit one message (assumed constant). Thus $S < 1$. Both half-amplitude and zero capture were considered. When half-amplitude was analyzed, it was assumed that the attenuation from repeater $i + 1$ to repeater i was less than that from repeater $i - 1$ to repeater i. Hence, a transmission from repeater $i+1$ to repeater i cannot be destroyed by a subsequent transmission from repeater $i - 1$. However, a transmission from repeater $i - 1$ to repeater i will be destroyed by a subsequent overlapping transmission from repeater $i + 1$.

These results were obtained by applying models based on work primarily by Tobagi and Kleinrock [2], as well as by developing new models of our own. The initial results, which are summarized in Table 5.1, are referred to as asymptotic because a large number of tandem repeaters are assumed. First, ALOHA is shown to have a greater throughput capacity (0.5 versus 0.4) than CSMA with perfect scheduling, i.e., no collisions. ALOHA is superior because there are times when CSMA will reschedule a transmission when it is not necessary. Although these throughputs cannot be realized, they do establish upper bounds on obtainable throughput. These results are derived in Section 5.2. Also, as discussed in Section 5.3, under full capture with CSMA, throughput is estimated as 0.25, but this is regarded as optimistic.

The remainder of the results compare slotted ALOHA, unslotted ALOHA, and CSMA with zero capture and half-amplitude capture. The CSMA results are based on results of Tobagi and Kleinrock [2] and are derived in Section 5.3; the ALOHA results are derived in Section 5.4. With either half-amplitude or no capture, slotted ALOHA is uniformly the best

FIGURE 5.1: TANDEM REPEATER (ONLY ADJACENT UNITS CAN COMMUNICATE)

TABLE 5.1: ASYMPTOTIC CAPACITY OF TANDEM REPEATER NETWORKS

ACCESS SCHEME	CAPACITY
PERFECT SCHEDULING - ALOHA	0.5
PERFECT SCHEDULING - CSMA	0.4
CSMA - "FULL" CAPTURE	0.25
SLOTTED ALOHA - 1/2 AMPL. CAPTURE	0.180
CSMA - 1/2 AMPL. CAPTURE	0.168
SLOTTED ALOHA - NO CAPTURE	0.15
CSMA - NO CAPTURE	0.137
UNSLOTTED ALOHA - 1/2 AMPL. CAPTURE	0.088
UNSLOTTED ALOHA - NO CAPTURE	0.078

technique, while unslotted ALOHA is uniformly the worst. Maximum throughputs of 15 to 20% are expected. Since the synchronization required for slotted ALOHA may not readily be implementable in a network environment, it would appear CSMA is the superior alternative. However, the CSMA results are based on results derived by Tobagi and Kleinrock and include some optimistic assumptions.

In Section 5.5, a more detailed analysis is performed, which eliminates the asymptotic assumption. The exact analysis of a three-repeater network analysis operating with CSMA and half-amplitude indicates a maximum throughput of 0.268 versus 0.365 predicted by results based on the Tobagi and Kleinrock model. From this we conclude that the CSMA throughput estimates are optimistic and that the superiority of CSMA over ALOHA in a network environment is marginal.

Then in Section 5.6, a lower bound is derived for the throughput that the C2 network can support. The bound indicates that with high confidence, the network can support the offered load in the scenario.

5.2 Perfect Scheduling Analysis

First we investigate the best that can be done if perfect scheduling is possible. Consider the chain in Figure 5.2(a), where specific streams have been labelled with the letters A to G. We schedule the A messages in an interval (average) of length S. The B messages, to be successful, cannot overlap with A, and so they require a second interval of length S. Similarly, C and D require additional intervals, as depicted in Figure 5.2(b).

Consider the ALOHA access method. E cannot be scheduled with A because node 2 can hear both. But E can be scheduled simultaneously with B, although nodes 2 and 3 hear both transmissions, only nodes 1 and 4 can receive the messages. Similarly, F and A can transmit simultaneously, and so on. Thus we have $4S \leq 1$ or $S \leq 1/4$. Defining capacity, C, (per node) as a maximum value of 2S, we have C = 0.5 for perfect scheduling in ALOHA. This is true if we use slotted or unslotted ALOHA, whether or not we allow half-amplitude capture.

Next, consider CSMA. We assume that the propagation time between neighbors is small enough to be negligible, i.e., that neighbors instantaneously hear each others' transmissions. The arguments proceed as above for A, C, D, and F and are illustrated in Figure 5.2(c).

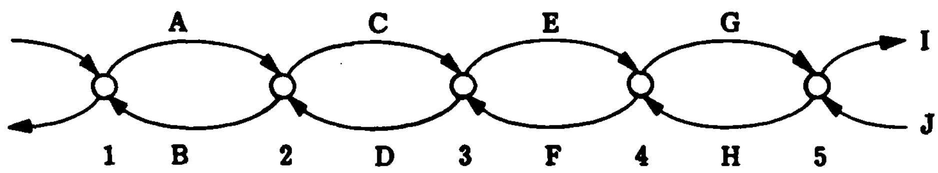

FIGURE 5.2(a): TANDEM REPEATER LABELED INFORMATION FLOW

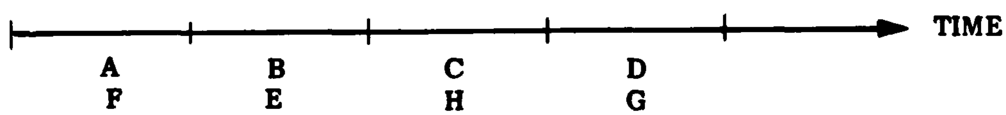

FIGURE 5.2(b): POSSIBLE ALOHA SCHEDULING STRATEGY

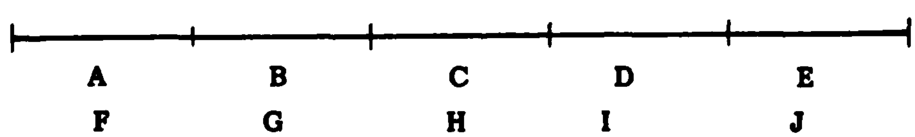

FIGURE 5.2(c): POSSIBLE CSMA SCHEDULING STRATEGY

But here, E and B cannot be transmitted simultaneously because of CSMA. (A more elaborate scheme could be used to allow this.) But G and B and H and C can be transmitted together. Thus, $5S \leq 1$, $S \leq 0.2$, and $C = 0.4$ for perfect scheduling in CSMA. This is less than with ALOHA because of the times CSMA prevents transmission, even though it could have been successful (E and B).

5.3 Tandem Repeaters Using CSMA

In this section the hidden terminal analysis of Tobagi and Kleinrock [2] is extended to the tandem repeater network using CSMA. Because of the hidden-terminals effect, this analysis is approximate and is believed to give results which are optimistic, i.e., resultant capacities are too high; more refined analyses are presented in Section 5.5. Consider a group of terminals, all of which can hear each other, so there are no hidden terminals. As a group they wish to send messages at a rate S to a station which is also in hearing range. We model this source of messages as a Poisson process. Since each terminal can hear each other terminal simultaneously, they will not transmit until the channel is idle. There will be no collisions (assuming instantaneous propagation). If a message is not transmitted, it is rescheduled at a random later time in the "far" future. The total stream of scheduled messages (actual transmissions plus blocked transmissions) can also be modeled as a Poisson stream of rate $G \geq S$. Consider the channel occupancy. A message is transmitted successfully for 1 time unit (normalized). Then, the channel is idle for an exponential time of average length 1/G. Thus, the probability that the channel is idle is

$$\frac{1/G}{1+1/G} = \frac{1}{1+G}$$

and is exact for this model. A scheduled message is transmitted successfully if the channel is idle. Thus, the probability of success is $\frac{S}{G} = \frac{1}{1+G}$, or $S = \frac{G}{1+G}$, and the maximum is $S = 1$. Obviously, this can be achieved only in the limit as G becomes infinite. Thus, the success probability S/G goes to zero and delays become infinite.

The existence of hidden terminals will lead to collisions. Tobagi and Kleinrock then assume terminals are grouped according to their connectivity, i.e., all members of a group can hear each other and the same other terminals. A terminal will transmit if its group is idle and its neighboring groups are idle. Otherwise, it will reschedule the message.

Consider the effect of the neighboring groups on this decision. Let G' be the rate of scheduled messages that are not blocked by the neighbors; G is the rate of scheduled transmissions. Then (approximately), G' plays the role of G above. They assume that the probability of being idle is $\frac{1}{1+G'}$. Furthermore, they assume (optimistically) that each group is independently idle. Then, if N_i is the set of neighbors of group i,

$$G_1' = \prod_{j \in N_i} \frac{G_i}{(1+G_j')}.$$

Now consider the transmission of a message from group i to the station. A scheduled message will be transmitted by group i successfully to a station if it is transmitted at all, i.e., its group and its neighbors are idle, and if no other groups (hidden from the transmitting group) transmit during the transmission time. These probabilities can be immediately evaluated as:

$\frac{1}{1+G_i'}$ - Group i is quiet when transmission is initiated

$\prod_{k \in N_i} \left(\frac{1}{1+G_k'}\right)$ - Its neighbors are quiet

$\prod_{k \notin K} \left(\frac{1}{1+G_{k'}}\right)$ - The hidden terminals are quiet where $K = N_i \cup \{i\}$.

$\prod_{k \notin K} e^{-G'_k}$ - The hidden terminals do not begin transmitting after group i has initiated transmission.

Then, assuming independence, the probability of success is:

$$\frac{S_i}{G_i} = \frac{\prod_{k \notin N_i \cup \{i\}} e^{-G'_k}}{\prod_{\text{all } j} (1+G'_j)}$$

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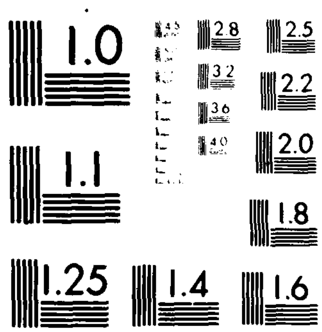

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In the above, the probability that a packet radio does not transmit is approximated by $e^{-G'_k}$. Thus, the transmitted stream is also assumed to be Poisson.

For our problem, there are no stations; each group essentially consists of a single terminal. Hence, the above analysis does not directly apply. In our problem, after the routing is distributed, the rate of transmission S_{ij} between neighboring terminals can be determined. We will assume that all these message streams are independent and Poisson. Furthermore, let $D_{ij}\, \epsilon (N_j \cap \bar{N}_i)$ be the terminals which dominate a transmission from i to j, in the sense of half-amplitude capture, where the bar denotes set complement. If d_{ij} is the distance between i and j, and if proximity determines capture, then $k \epsilon D_{ij}$ if $k \epsilon N_j$, $k \notin N_i$, and $d_{kj} < d_{ij}$. Also assume separate (Poisson) streams for scheduled and unblocked messages at each node for each destination. Then,

$$\frac{S_{ij}}{G_{ij}} = \frac{\prod_{k \epsilon D_{ij}} e^{-G'_k}}{\prod_{\ell \epsilon N_j \cup N_i} (1+G'_\ell)}$$

$$G_i = \sum_{j \epsilon N_j} G_{ij}$$

$$S_i = \sum_{j \epsilon N_j} S_{ij}$$

$$G_i' = G_i \frac{1}{\prod_{\ell \epsilon N_i} (1+G'_\ell)}$$

The above expression is similar to the previous analysis. However, in this case the numerator is defined noting that only devices that have energy greater than group i can interfere with a transmission from i to j; otherwise, they must remain silent. Also, the denominator is defined noting that terminals which i and j cannot hear are irrelevant (and

hence do not appear in the equation). The above approximate analysis can be applied to any topology. Consider the topology of Figure 5.1, where we assume that terminals to the left dominate. Using the above equations, we obtain after significant algebraic simplification:

$$\frac{G'_i}{1+G'_i} = S\left(1+G'_{i-2}\right)e^{G'_{i-2}} + \left(1+G'_{i+2}\right), \quad 3 \le i \le N-2$$

$$\frac{G'_i}{1+G'_i} = S\left(1+G'_3\right), \quad \frac{G'_2}{1+G'_2} = S\left(2+G'_4\right),$$

$$\frac{G'_{n-1}}{1+G'_{n-1}} = S\left[\left(1+G'_{n-3}\right)e^{G'_{n-3}} + 1\right], \quad \frac{G'_n}{1+G'_n} = S\left(1+G'_{n-2}\right)e^{G'_{n-2}}.$$

Assume that as $N \to \infty$, we reach a steady-state condition where $G'_i \to G'$. (We observed this behavior in an exact analysis of an ALOHA scheme). Setting all $G_i = G$, we have

$$S = \frac{G'}{(1+G')^2(1+e^{G'})}$$

which achieves a maximum of 0.084 at $G' = 0.5$. Thus, $C = 0.168$ for CSMA with half-amplitude capture. Again note that this analysis is approximate and probably optimistic. The actual capacity will be less.

It is easy to determine the effect of half-amplitude capture with this analysis. The above equation can be rederived. Let G_1 (G_2) be the scheduled stream to the right (left) for a typical terminal. Then,

$$\frac{S}{G_1} = \frac{1}{(1+G')^4}, \quad \frac{S}{G_2} = \frac{e^{-G'}}{(1+G')^4}, \quad G = G_1 + G_2, \quad G' = \frac{G}{(1+G')^2}.$$

For no capture, the first term becomes

$$\frac{S}{G_1} = \frac{e^{-G'}}{(1+G')^4} \quad \text{and} \quad S = 1/2\, \frac{G'e^{-G'}}{(1+G')^2}$$

which has a maximum of 0.0684 at G' = 0.4. Thus, without capture, C = 0.137. Similarly, if somehow we can achieve "full" capture, the second term becomes

$$\frac{S}{G_2} = \frac{1}{(1+G')^4} \quad \text{and} \quad S = 1/2\, \frac{G'}{(1+G')^2}$$

which has a maximum of 0.125 at G' = 1. Thus, C = 0.25 if we can have "full" capture. These results are summarized in Table 5.1.

5.4 Tandem Repeaters Using the ALOHA Access Method

In this section an exact analysis of an ALOHA-type access scheme is presented. Consider first the case of unslotted ALOHA with half-amplitude capture. We have modelled each terminal's traffic as one or two Poisson streams. If a terminal was operated in "pure" ALOHA, its transmissions would collide with themselves if they appear less than one transmission time apart. In traditional ALOHA analyses, one usually modelled a group of terminals that could not hear each other. If they could hear each other, then CSMA is ideal. Here, there is only one terminal in a group, and such collisions are in essence suicidal (also physically impossible) and should not be allowed.

We now modify the access scheme at a terminal. This is essentially a revision of the message-stream process. The original message stream is Poisson with a rate S. If any messages should collide because they are too close together, they are rescheduled at a random time in the far future. Any messages which are transmitted and collide with messages from other terminals are also rescheduled, as above. The resultant transmitted message stream has a rate $G \geq S$ because of these collisions, and the stream is no longer

Poisson. Consider channel occupancy again. A message transmission takes one time unit (normalized). The time to the next message is exponential (by the above assumptions) with, say, mean $1/G^*$. The fraction of time that the repeater is transmitting is

$$G = \frac{1}{1+1/G^*} = \frac{G^*}{G^*+1}, \quad \text{or} \quad G^* = \frac{G}{1-G}.$$

Thus, the repeater is idle with probability 1 - G and will not transmit in a unit transmission interval with probability $e^{-G/(1-G)}$. The important aspect of this model is that every terminal operates independently.

Assuming half-amplitude capture as before, and letting G_1 (G_2) represent the stream to the right (left), we have

$$\frac{S}{G_{i1}} = (1 - G_{i+1})\left\{\exp - \left(\frac{G_{i+1}}{1-G_{i+1}}\right)\right\}(1 - G_{i+2})$$

$$\frac{S}{G_{i2}} = (1 - G_{i-1})\left\{\exp - \left(\frac{G_{i-1}}{1-G_{i-1}}\right)\right\}(1-G_{i-2})\left\{\exp - \left(\frac{G_{i-2}}{1-G_{i-2}}\right)\right\}$$

$$G_i = G_{i1} + G_{i2}$$

$$3 \leq 1 \leq N - 2$$

with obvious changes for $i = 1, 2, N-1, N$. Note that we assume in the above that a terminal can decide to transmit while receiving, and thus force a collision. This was done to preserve independence between terminals. If all $G_i \to G$ when $N \to \infty$, as above, then

$$S = \frac{G(1-G)^2 e^{-2G/(1-G)}}{1+e^{-G/(1-G)}}$$

which achieves a maximum of 0.044 when G = 0.2. Hence, the capacity is 0.088. Without capture, similar analysis yeilds

$$S = 1/2\, G(1-G)^2 \; e^{-2G/(1-G)}$$

which achieves a maximum of 0.039 at G = 0.18; hence, C = 0.078.

In a similar fashion, a slotted ALOHA scvheme can be analyzed. Again assume that if a terminal has already scheduled a transmission in a slot, it will reschedule any other messages that fall in that slot. Then, terminals again act independently. Let P be the probability that a terminal will transmit in a slot. Assuming that capture can take place rapidly, we again consider half-amplitude capture as discussed above. 1 - P is now the probability that a terminal is idle. For $N \to \infty$

$$\frac{S}{P_1} = (1 - P)$$

$$\frac{S}{P_2} = (1 - P)^2$$

$$P = P_1 + P_2$$

$$P = \frac{S}{1-P} + \frac{S}{(1-P)^2}$$

Thus, where P_1 is the probability that repeater i is transmitting to repeater i + 1, and P_2 is the probability that repeater i is transmitting to repeater i - 1,

$$S = \frac{P(1-P)^2}{2-P}$$

which achieves a maximum of 0.0902 at P = 0.38. Hence, C = 0.18. Without capture,

$$S = 1/2\ P(1 - P)^2$$

and achieves a maximum of S = 2/27 at P = 1/3; hence, C = 0.15.

From these preliminary analyses, it is seen that slotted ALOHA, properly modified, is slightly better than CSMA, and that unslotted ALOHA has approximately half the capacity. Other access schemes and more refined analyses are possible. However, it should be noted that if echo acknolwedgments were to be included in the analysis, the performance of the ALOHA schemes would degrade more than that of CSMA.

5.5 Tandom Network Using CSMA (Exact Methods)

This analysis is more refined in that the results do not require the number of repeaters to become arbitrarily large.

5.5.1 Three Repeater Problem

To get a better feel for the approximations in the approach based upon Tobagi and Kleinrock's work, we have developed alternate analytic techniques for this project. First consider a small chain with N = 3. Let P_I equal the probability that the entire system is idle, and consider CSMA with half-amplitude capture as defined above. Then,

$$\frac{S}{G_1} = P_I = \frac{2S}{G_2}, \frac{S}{G_3} = P_I\ e^{-G_1}$$

where G_i are the Poisson rates of the scheduled traffic, 1 dominates 3, and e^{-G_1} is the probability that 1 does not collide with 3. Let I_k be the event that the k^{th} repeater is idle at an instant, k = 1,2,3. Since packets from repeater 2 never collide, $P(I_2) = 1-2S$. Also,

$$P_I = P(I_1 I_2 I_3) = P(I_1 I_3 | I_2)\ P(I_2)$$

It can be shown that

$$P(I_1 I_3 | I_2) = P(I_1 | I_2)\ P(I_3 | I_2)$$

The argument is essentially that when repeater 2 is idle, the other repeaters are operating independently. It can also be shown by similar arguments that

$$P(I_1 | I_2) = \frac{1}{1+G_1}, \quad P(I_3 | I_2) = \frac{1}{1+G_3}$$

which is the same expression as if each repeater were acting alone. From the above results, S can be determined as

$$S = \frac{G_1}{(1+G_1)(1+G_1 e^{G_1}) + 2G_1}$$

This expression has a maximum of 0.134 when $G_1 = 0.5$. Thus, C = 0.268. This is an exact result. From the techniques based upon Tobagi and Kleinrock's methods, we obtained a capacity of C = 0.365 for the same problem. Thus, it is believed that their results are optimistic. Note that we apply the results of Tobagi and Kleinrock in a fashion probably not anticipated by them, and the above comments are not intended as criticism of their work.

These results can be generalized to a star configuration where an arbitrary number of repeaters all home on a single site as depicted in Figure 5.3. In this case

$$P(I_1) = 1 - 2nS$$

where

- PRU one is the hub

- There are n surrounding PRU's.

Similar independence results can be established showing

$$P(I_i I_j | I_1) = P(I_i | I_1)\, P(I_j | I_1) \qquad i \neq j \quad i \neq 1, j \neq 1$$

$$P(I_j | I_1) = 1/(1+G_j).$$

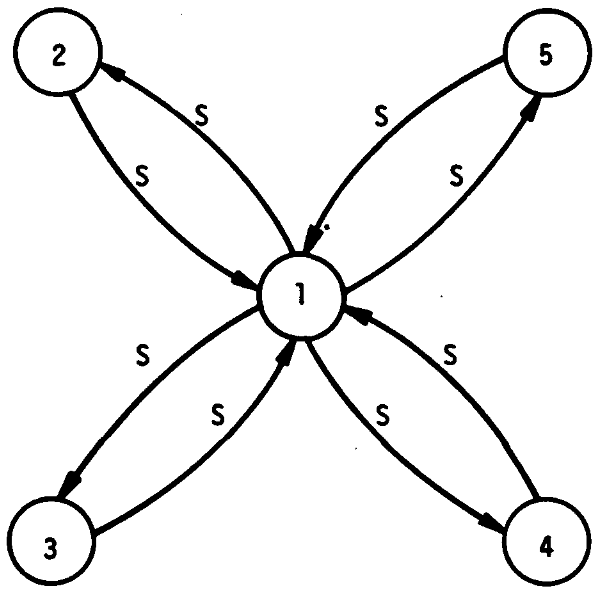


FIGURE 5.3: STAR NETWORK (n = 4)

$$\frac{S}{G_i} = P_I e^{-(n-1)G_i}$$

$$\frac{nS}{G_1} = P_I$$

under the assumption of no capture.

5.5.2 Multiple Tandem Repeater Analysis

We assume that routing has been accomplished and the packets scheduled for transmission from a node to its neighbor are represented by a Poisson stream, which is independent of all other such streams, i.e., going to another neighbor or at another node. These scheduled packets may or may not be transmitted. If when a packet is scheduled, the transmitting node and all its neighbors are idle, then the packet will be transmitted. If not, the packet will be rescheduled at a random time in the future. A transmitted packet will be successfully received if in addition all of the neighbors of the receiving node are idle and none of them begin transmission for the duration of the packet. (When half amplitude capture is in effect, some of the neighbors may transmit without destroying reception.) If packets are unsuccessfully transmitted, or cannot be transmitted, or if acknowledgments are not heard, the packets must be rescheduled. We assume that all rescheduling is at a long and random future time so that the entire scheduled stream of traffic is Poisson. Thus we model the traffic as independent Poisson streams at each node. Let n_i be a neighbor of node i. Then G_{i,n_i} is the rate of the scheduled traffic from i to n_i. All the streams, for every i and n_i, are assumed independent. The total scheduled traffic at a node is also Poisson and has a rate

$$G_i = \sum_{n_i} G_{i,n_i} \quad .$$

The performance of the network depends upon the status of the nodes when a packet is scheduled. Let A denote a set of nodes and P(A) the probability that <u>all</u> nodes in A are idle. If B is another set of nodes, then $P(A,B) = P(A \cap B)$; and $P(A \mid B)$ is the probability that all nodes in A are idle given that all nodes in B are idle. We can now provide some general results.

let N_i be the set of all neighbors of a node i. Then for any $A \subseteq N_i$,

$$P(i,A) = P(i) + P(A) - 1. \tag{1}$$

To prove this result, note that $P(A) = P(i,A) + P(\bar{i},A)$, where $\bar{i}$ denotes that i is busy (not idle). Then $P(i,A) = P(A \mid i)P(i)$. However, $P(A \alpha i) = 1$ and $P(i) = 1 - P(\bar{i})$.

A node i will transmit when i and all nodes in N_i are idle when a packet is scheduled. If the length of a message (or its average length) is normalized to unity, then

$$P(\bar{i}) = 1 - P(i) = G_i P(i,N_i). \tag{2}$$

To understand this equation, note that $G_i\ P(i, N_i)$ is the rate of the actual transmissions because i will transmit if and only if i is idle and its neighbors N_i are idle. Consider a long time period T, then the fraction of time during T that i will be transmitting is

$$P(\bar{i}) = G_i\ P(i, N)\ T/T.$$

The result follows immediately, noting the cancellation of T.

Now G_i is the scheduled packet rate in units of packets per (average) packet transmission time. Letting $A = N_i$ above in (1), combine with (2) and apply definition of conditional probability, we get

$$P(i \mid N_i) = \frac{1}{1+G_i}\ . \tag{3}$$

Note this established the independence results in Section 5.4.

We consider first exponential packet lengths, again normalized to unity. The evolution of the network is now completely characterized by a continuous time Markov chain. Let D be a disjoint set of nodes, i.e., none of which are neighbors. Let $\mathcal{D}$ be the class of all sets D, including $\emptyset$, the null set. Let D be the event (state) that all nodes in D are busy and all nodes not in D are idle. Then $\emptyset$ denotes the event that all nodes are idle. Let N be the set of all nodes in the network. These states form a Markov process. The transition equations are

$$\left(\sum_{i \in N} G_i\right) P(\emptyset) = \sum_{i \in N} P(\bar{i}) \tag{4}$$

For $D \neq \emptyset$, and $d = |D|$, the cardinality of D, and f(D) the set of nodes that are disjoint with all nodes in D,

$$\left(d + \sum_{j \in f(D)} G_j\right) P(D) = \sum_{i \in D} G_i P(\{D - i\}) + \sum_{j \in f(D)} P(\{D + j\}) \tag{5}$$

It is relatively easy to see that these equations are solved by

$$P(D) = \left(\prod_{i \in D} G_i\right) P(\emptyset) \tag{6}$$

$P(\emptyset)$ is the probability that all nodes are idle and is given by

$$P(\emptyset) = \left[1 + \sum_{D \in \mathcal{D} - \emptyset} \prod_{i \in D} G_i\right]^{-1} \tag{7}$$

With these results, the probability of any occurrence in the network can be determined in terms of the $\{G_i\}$. For example, let the set of nodes and Q be the set of sets D containing none of the nodes in A, including $\emptyset$, then

$$P(A) = \sum_{D \in Q} P(D) \tag{8}$$

These probabilities can now be related to the successful transmission rates from each node. Let S_{i,n_i} be the rate of successful transmissions from a node i to its neighbor n_i. Then

$$\frac{S_{i,n_i}}{G_{i,n_i}} = P(N_i, N_{n_i}) Q_{i,n_i} \tag{9}$$

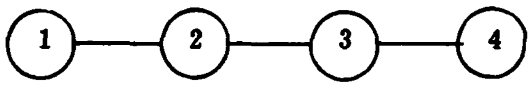
Note that for a scheduled packet at i to be sent N_i and i must be idle and $i \in N_{n_i}$. For this packet to be received at n_i initially then N_{n_i} and n_i must be idle and $n_i \in N_i$. Then

Q_{i,n_i} = P(during a transmission time no neighbors of n_i transmit that are not dominated by i | N_i, N_{n_i}, and i is transmitting).

The probabilities Q_{i,n_i} can be computed for exponential packet lengths. The above equation is valid for constant packet lengths but Q_{i,n_i} is much harder to obtain, although bounds and approximations can be found.

Example 1:

(Assume half amplitude capture with left nodes dominating)



$$\frac{S_{12}}{G_{12}} = P(1,2,3) = \frac{S_{21}}{G_{21}}$$

$$\frac{S_{23}}{G_{23}} = P(1,2,3,4)$$

$$\frac{S_{32}}{G_{32}} = P(1,2,3,4)Q_{32}$$

$$\frac{S_{34}}{G_{34}} = P(2,3,4)$$

$$\frac{S_{43}}{G_{43}} = P(2,3,4)Q_{43}$$

$$G_1 = G_{12}, G_2 = G_{21} + G_{23}, G_3 = G_{32} + G_{34}, G_4 = G_{43}$$

$$P(1,2,3,4) = P(\emptyset) = \left[1 + G_1 + G_2 + G_3 + G_4 + G_1G_3 + G_1G_4 + G_2G_4 \right]^{-1}$$

$$P(1,2,3) = P(\emptyset) + P(4) = (1 + G_4)\ P(\emptyset)$$

$$P(2,3,4) = P(\emptyset) + P(1) = (1 + G_1)\, P(\emptyset)$$

Here we have assumed half-amplitude capture with left nodes dominating.

Q_{32} = P(1 doesn't transmit during a transmission time all nodes idle initially and 3 is transmitting).

Since 3 is transmitting 2 must be idle and 1 will transmit if scheduled. Thus Q_{32} is the probability that the packet ends before 1 transmits.

$$Q_{32} = \frac{1}{1+G_1}$$

Similarly,

Q_{43} = P (2 doesn't transmit during a transmission time | 2,3,4 idle initially and 4 is transmitting).

Since 4 is transmitting, 3 must be idle throughout. There will be a collision of 2 transmits before the packet ends. Node 1 may or may not be idle. If 1 is not idle, then 2 cannot transmit. Thus

$$1 - Q_{43} = P(1 \mid 2,3,4)\alpha + \left[1 - P(1 \mid 2,3,4)\right]\beta$$

$$\alpha = \frac{G_2}{1+G_1+G_2} + \frac{G_1}{1+G_1+G_2}\,(1/2)\ \alpha$$

$$\beta = 1/2 \ \alpha$$

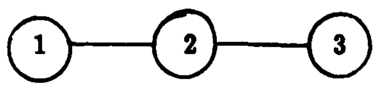
Here α = P(2 transmits before packet ends | 1,2,3,3) and can occur if 2 transmits first or 1 transmits first, ends before the packet ends, and then 2 transmits first. β is defined similarly.

β = P(2 transmits during the period |1,2,3,4)

The equations can not be solved for $\{S_{i,j}\}$ in terms of $\{G_{i,j}\}$. Maximum values of $S_{i,j}$ can be found to determine capacity. The effects of passive acknowledgments can also be evaluated. This will relate the $\{S_{i,j}\}$ to the actual end-to-end successful transmission of packets. $S_{i,j}$ will then include repetitions. The same procedures can be used for any network topology.

<u>Example 2:</u>

(Again assuming half-amplitude capture with left nodes dominating.)



$$\frac{S_{12}}{G_{12}} = P(1,2,3) = \frac{S_{21}}{G_{21}} = \frac{S_{23}}{G_{23}} = P(\emptyset) = \left[1 + G_1 + G_2 + G_3 + G_1G_3\right]^{-1}$$

$$\frac{S_{32}}{G_{32}} = P(1,2,3)\,\frac{1}{1+G_1} = P(\emptyset)\,\frac{1}{1+G_1}.$$

Let $S_{12} = S_1, G_{12} = G_1, S_{21} + S_{23} = S_2, G_{21} = G_{23} = G_2, S_{32} = S_3, G_{32} = G_3$.

Then

$$\frac{S_1}{G_1} = \frac{S_2}{G_2} = \frac{S_3}{G_3}(1 + G_1) = \left[(1 + G_1)(1 + G_3) + G_2\right]^{-1}.$$

For specifity, let $S_1 = S, S_2 = 2S, S_3 = S$.

Then

$$G_2 = 2G_1, G_3 = G_1(1 + G_1), \text{ and}$$

$$S = \frac{G_1}{(1+G_1)\left[1+G_1(1+G_1)\right] + 2G_1} = \frac{G_1}{1 + 4G_1 + 2G_1^{\,2} + G_1^{\,3}}$$

The *maximum* value *of* S *found* to be 0.138 *for* $G_1 = 0.6$.

The above analysis assumes exponential lengths for the packets. There are some unusual consequences of the exponential model however. We have seen that a similar analysis of a three-node chain with constant packet lengths results in a throughput of 0.1348 which is slightly worse than that for the exponential assumption. The reason is that smaller packets are more likely to be successfully received. But the throughput here, S, is in packets/average transmission time. When the lengths of the successful packets are considered, the exponential assumption results in a lower throughput, at least in the example below.

The dependence of probability of success on packet length refers only to those collisions due to the "capture" effect. For the three nodes chains above, assume 3 is transmitting to 2. This will happen if 2 and 3 are idle. If 1 is also idle, 2 will begin to receive. So far, the length of the transmission has not played a role. But there will be a collision if 1 schedules (and transmits) a packet before 3 finishes, and this does depend upon packet length.

Let P_{32} be the probability of successfully sending a packet from 3 to 2. This was S_{32}/G_{32} above. Let $P_{32}(x)$ be the probability given that the transmitted packet has length x. Then

$$P_{32}(x) = P(\emptyset)\, e^{-G_1 x}$$

Averaging over all packet lengths we get

$$P_{32} = \int_0^\infty P_{32}(x)\, e^{-x}\, dx = P(\emptyset)\frac{1}{1+G_1} = \frac{S_{32}}{G_{32}}$$

as it should.

When a packet of length x is successfully received, then x bits (normalized) are delivered. The successful "bit" rate (normalized) is given by

$$G_{32} \int_0^\infty x P_{32}(x)\, e^{-x}\, dx = G_{32} P(\emptyset) \frac{1}{(1+G_1)^2} = \frac{S_{32}}{1+G_1}.$$

This compares to S_{32} for the bit rate when the packet lengths are constant. The value of G_1 that gives the maximum throughput will be different however. For the exponential lengths we get a bit rate of .096 when $G_1 = 0.3$. Thus the throughput in bits is indeed less than that for constant packet length.

There are other consequences of this phenomenon. The exponential packet lengths in this model are independently regenerated for every transmission for the same message. Thus eventually a small length will be tried and the probability of success enhanced.

5.6 Application: A Loose Bound on Performance

Consider a general network with a host, i.e., all traffic directed to or from a specific node, operating under CSMA with half-amplitude capture and including the effect of passive acknowledgments. We can replace this network with a simpler network with a much lower throughput and thus derive a loose lower bound on the throughput.

The network operating as defined above (CSMA, etc.) should perform no worse than if unslotted ALOHA was used. (If not, then CSMA should be replaced by unslotted ALOHA.) Thus, we consider unslotted ALOHA for the network to derive the lower bound. We find a set of minimum hop paths for the network. Again, we need not find the best routing since we are looking for a lower bound. However, the bound will be tighter if a better routing is found.

Consider two nodes both i hops away from the host. They may or may not hear each other and may or may not hear the same set of neighboring nodes; note, a node at hop i, in a minimum path route, can only hear other nodes at hops $i - 1$, i, and $i + 1$. These two nodes may simultaneously receive or simultaneously transmit if they are corresponding with disjoint neighbors. If we merge these nodes, i.e., replace them by a single node with the aggregate traffic and a set of neighbors equal to the union of the neighbors of each, then under an unslotted ALOHA discipline, the performance cannot have been improved. (In CSMA, however, the performance could have been improved because there will be less collisions.) This step can be repeated until we are left with a chain of nodes with the host at one end. The length of the chain is that of the longest path in the min hop routing. The traffic to and from a node in the chain is the sum of the traffic of all nodes at the same hop level in the min path routing.

This chain can be analyzed using unslotted ALOHA. For simplicity, we move all traffic to the end nodes and consider, S, the larger of the two rates, one for each direction.

Thus the chain is modeled as attempting to send S packets/second from the host to the last node in the chain and S packets/second in the reverse direction. S is the larger of the sums of all traffic for all nodes in either direction. The performance is certainly not better than if each node is permitted to have different requirements. This step need not be taken if the resultant bound is too loose.

Consider the host which is attempting to send S packets/second. Because of collisions with itself and the next two nodes (for the bound we consider zero-capture here) and because of failure to hear passive acknowledgments, packets will have to be repeated. As a worst case, we assume that all packets will be repeated exactly K times where K is the maximum number of tries allowed in the protocol. However, the next node will notice repetitions and attempt to transmit only one copy. Thus the rate of scheduled messages at the host, G_1, which is in general bounded by KS, is here set to KS. Not all the messages will be successfully received by the next node. Thus, its transmission rate will be less than S. Again, assume the worst, set it equal to S, and the scheduled rate of intermediate nodes, in each direction, is at most KS. The total scheduled rate at each intermediate node is thus G = 2KS. For simplicity, we inflate the scheduled rate at the end nodes to 2KS also.

For all but the last node in a chain, there will be a collision if during a transmission the sending node or the receiving node or the next node is already transmitting or begins to transmit. These nodes thus cannot successfully transmit a packet in an interval of two transmission times surrounding the start of transmission of the packet in question. We here assume constant transmission times and normalize G and S to rates in packets/unit transmission time. We also assume that all streams are Poisson and independent. Thus, the probability of no transmission in the interval by any node is given by $e^{-6G} = e^{-2(2KS)}$. To be successful, three successive nodes must be quiet, thus the probability of success is $e^{-6G} = e^{-12KS} \triangleq P$. For the last transmission in the chain, only two nodes need be quiet, but again for simplicity we use the smaller P above.

Since a packet will be repeated at most K times, the probability of successfully transmitting a packet over a link is at least $1 - (1 - P)^K$. The probability of transmitting a packet successfully over ℓ hops is $q = \left[1 - (1 - P)^K\right]^{\ell}$, where $P = e^{-12KS}$.

To apply these results, it is first necessary to compute the network traffic volume during the peak hour in units of bps. The traffic rate (including overhead) can be determined as follows

$$T = \frac{M}{3600}\left[\, IP + n(Poh) + n(ETE)\right]$$

where

$$T = \text{Traffic volume in bps during peak hour.}$$

$$M = \text{Number of messages during peak hour.}$$

$$IP = \text{Text length of message.}$$

$$n = \text{Number of packets per message (3).}$$

$$Poh = \text{Packet overhead (448 bits).}$$

$$ETE = \text{End-to-end acknowledgment size (448).}$$

These traffic calculations are summarized in Table 5.2. As indicated in the table, the peak hour rate from PRU's to the host is 1065 bps while the peak hour rate from the host to the PRU's is 1035 bps. Since the first value is larger, it is used as the throughput constraint in the above model. Thus with a 100 Kbps data rate, the network must support a throughput of S = 0.01065.

For a 3 hop network with 3 transmissions,

$$P = e^{-12KS}$$

$$P = e^{-12(3)(.01065)}$$

$$P = .698$$

Then

$$q = \left[1 - (1 - p)^{K}\right]^{P}$$

$$= \left[1 - (1 - .698)^{3}\right]^{3}$$

$$= .92$$

Thus with confidence greater than 0.92, a three-hop network can support a throughput S = .01065.

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TABLE 5.2: C^2 TRAFFIC VOLUME HOST SCENARIO

	PRU→HOST	HOST→PRU
Transmit Messages During 30 Hours	4692	4692
Direct Messages During 30 Hours	2742	2534
Total Messages During 30 Hours	7434	7226
Total Messages During Busy Hour	595	578
Information Packet Overhead Bits/Packet	448	448
ETE ACK (Bits/ACK)	448	448
Message Size (Information Bits)	3760	3760
Bit Rate (bps)	1065	1035

6. SURVIVABILITY MODELS

In the initial analysis of network connectivity using the Longley-Rice mean attenuation model, the PR nets were sparsely connected. At this time, it appeared that survivability was a major problem. Thus the analysis described below was performed to determine how many repeaters would have to be introduced to guarantee a certain level of survivability. However, with both the random Longley-Rice and LOS link models, there is substantially more connectivity and survivability is not a major problem.

Typically, a minimal number of repeaters are required, and their selection can be "eyeballed." For example, in the C^2 subnetwork (initial deployment), two repeaters were selected by MITRE with locations

- Repeater 1: 500 210
- Repeater 2: 590 394.

The critical devices in the C^2 network are the Maneuver Battalions. Without these repeaters, the Maneuver Battalions 1-78, 1-81, and 1-79 were essentially isolated having only one link connecting them with the rest of the network. Clearly, this would be an unacceptable level of survivability. However, with the introduction of dedicated repeaters, each of these devices could communicate with the rest of the network via 3 different paths. Thus, they would be isolated only if 3 devices failed. MITRE has estimated that the survival probability of all devices is greater than 0.95; thus, the probability of a Maneuver Battalion being able to communicate with the rest of the network is greater than

$$1 - (1 - P)^3 = .9998$$

for P = .95. Thus, we could conclude survivability is not a major problem. The models described below were developed when it was believed that the network connectivity was sparse. We have examined three models for insuring a specified survivability level. In all cases specified, survivability levels can be achieved by appropriate placement of nodes. In the following, we assume nodes fail independently with a uniform rate p. We consider the probability of two nodes, s and d, separated by paths with h intermediate nodes being able to communicate.

6.1 Models

6.1.1 Model A: Independent Paths

In this model (see Figure 6.1), we assume that all paths from s to d are independent. In particular, we assume that a node on one path cannot communicate with any node on another path. Thus, communication from s to d can only take place if an entire path remains intact. The probability of a single path working is $s_h = (1 - p)^h$. Let s = the probability of at least one of r such paths working is $1 - (1 - s_h)^r$. If $s_h << 1$ and $r >> 1$, this probability is approximately $1 - e^{-rs_h}$. Thus, given a desired survivability, R, and values for p and h (hence s_h), we find r is given approximately by:

$$r \approx \frac{\ln\left(\frac{1}{1-R}\right)}{s_h} = \frac{\ln\left(\frac{1}{1-R}\right)}{(1-p)^h}$$

Thus, r grows exponentially with h and if p is significant (say 0.2), r grows very quickly, as shown in Table 6.1 which gives exact values of r required for survivability of .95 and for typical values of p and h. We conclude that independent paths do not provide a sufficient level of survivability for reasonable values of r; some form of overlap among paths is required. The model of independent paths is useful, however, as it is a worst case for a given value of h and a given number of nodes.

6.1.2 Model B: Fully Connected Groups

This model represents the opposite extreme from the previous one. For most situations, the best one can do given that one can place only hr nodes, all nodes fail independently with probability p, and all paths must have h or more intermediate nodes in cascade, is (see Figure 6.2) to place the nodes in h groups of r such that all nodes in each group can communicate with one another and with all nodes in the preceeding and succeeding groups. The probability of all nodes in a group of r nodes all failing is p^r. Thus the probability of s and d being able to communicate is $(1 - p^r)^h$. If $hp^r << 1$, this is approximately equal to $1 - hp^r$. Thus, given a desired and values for p and h, we find

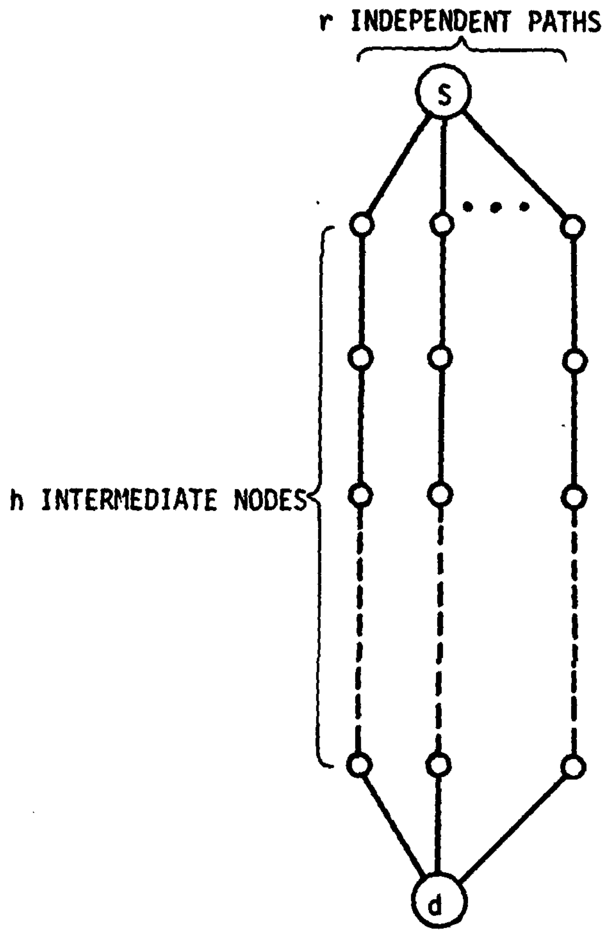

FIGURE 6.1: INDEPENDENT PATHS (LINKS INDICATE PAIRS OF NODES WHICH CAN DIRECTLY COMMUNICATE)

TABLE 6.1: PATH REQUIREMENTS (r) FOR INDEPENDENT PATH MODEL
(Survivability Level .95)

	p = .05	p = .1	p = .2	p = .5
h = 2	2	2	3	11
h = 4	2	3	6	47
h = 6	3	4	10	191
h = 8	3	6	17	766
h = 10	4	7	27	3067

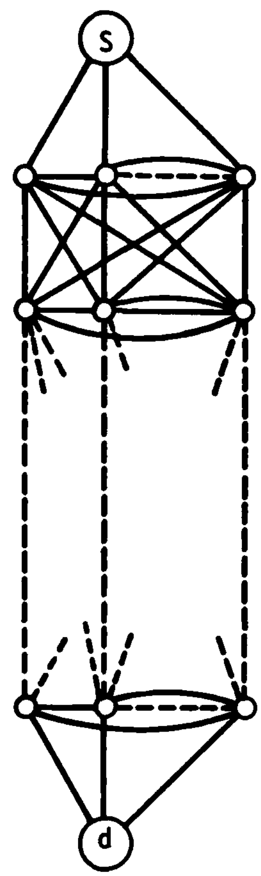

FIGURE 6.2: FULLY COMMUNICATING GROUPS

$$r \approx \frac{\log_2\left(\frac{1-R}{h}\right)}{\log_2 p}$$

Thus, r grows very slowly as a function of h. Table 6.2 gives (exact) values of r for typical values of p and h for R = .95.

6.1.3 Model C: Overlapping Chains

Finally, we consider (see Figure 6.3) a model which is neither an upper nor a lower bound on reliability, but rather, a representative model of a chain where non-adjacent nodes can communicate. In particular, we assume that each node can hear the r nodes immediately preceeding it and the r nodes immediately succeeding it in the chain. Thus s and d can communicate if no set of r adjacent node fail. Let c(h,r,p) be the probability that two nodes can communicate given there are h nodes in the chain separating them, nodes can communicate with r preceeding and r succeeding nodes, and nodes fail independently with probability p.

Then we can write the recurrence relation:

$$c(h,r,p) = \begin{cases} \sum_{i=1}^{r} (1-p)\, p^{i-1}\, c(h-i,r,p) & \text{for } h \geq r \\ 1 & \text{for } h \geq r \end{cases}$$

where the i^{th} term corresponds to node i working and nodes 1,...i-1 failing. (It is assumed that nodes s and d work.)

The general form of the recurrence relation is difficult to solve. Table 6.3 gives values of r for a survivability level of .95 and typical values of p and h.

6.2 Conclusions

There are two ways of obtaining the desired survivability given a number of nodes and a range over which communication can take place:

- add more nodes

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TABLE 6.2: GROUP SIZE (r) FOR FULLY-CONNECTED GROUPS

(Survivability R = .95)

	P = .05	P = .1	P = .2	P = .5
h = 2	2	2	3	6
h = 4	2	2	3	7
h = 6	2	3	3	7
h = 8	2	3	4	8
h = 10	2	3	4	8

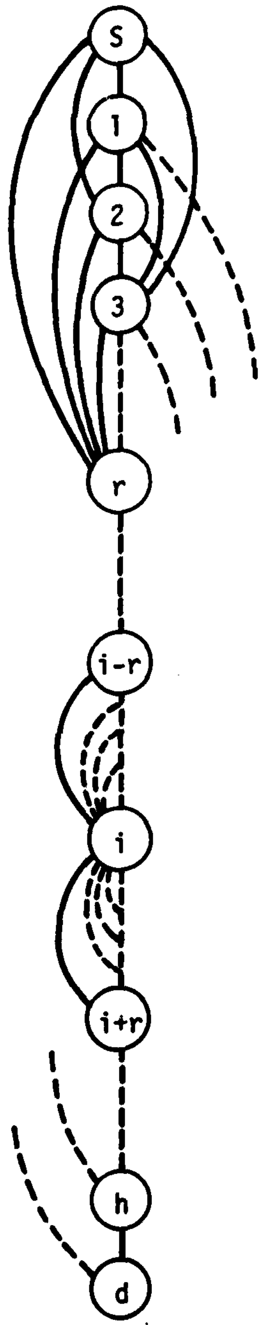


FIGURE 6.3: OVERLAPPING CHAINS

TABLE 6.3: REPEATER RANGE (r) FOR OVERLAPPING CHAINS

(Survivability Level = .95)

	P = 105	P = .1	P = .2	P = .5
h = 2	2	2	2	2
h = 4	2	2	3	4
h = 6	2	2	3	5
h = 8	2	3	3	3
h = 10	2	3	3	6

- increase the range.

We explore the effect of each of these using all three models, for R = .95.

Suppose s and d are 10 Km. apart and the range is 1 Km.

Case A: P = .05

Model A: 36 nodes required
(4 chains of 9 nodes 1 Km apart)

Model B: 18 nodes required
(9 groups of 2 nodes. Groups 1 Km apart)

Model C: 19 nodes required
(chain of 19 nodes .5 Km apart)

Case B: P = .2

Model A: 189 nodes required

Model B: 36 nodes required

Model C: 39 nodes required

Case C: P = .5

Model A: 13,797 nodes required

Model B: 72 nodes required

Model C: 99 nodes required

Thus, we see that for most situations of interest, Models B and C give very similar results.

The importance of this is that nearly the same survivability is obtained by employing a practical strategy (Model C) as can be obtained by an optimal strategy (Model B).

7. ROUTING

7.1 Overview

For the scenarios using LOS links and the scenario using direct-terminal communications, typically source and destination PRU were separated by at most two hops. In these cases, there is substantial connectivity and shortest arbitrary path routing is adequate.

However, in the host scenario using links determined by the random Longley-Rice model, more hops were required to traverse the network from origination to destination. For this case, a heuristic routing algorithm was developed. This algorithm, which is described below, provides shortest path routes but selects the shortest path in a way to minimize congestion. The computational complexity of this procedure is minimal and could easily be implemented in a PR station. Since only a few runs were made for this scenario, the algorithm was not implemented on the computer. Instead, the algorithm was executed manually and the resulting routes were entered into the computer. This exemplifies the minimal complexity of the procedure.

7.2 Motivation

The unusual nature of the network connectivity (as determined by the random Longley-Rice algorithm), in particular its relatively weak dependence upon distance, which arises from the random connectivity model makes the routing procedure described in the following sections necessary. The procedure is based on the following procedure which is suitable for networks with sparse traffic matrices and distance dependent connectivity.

Consider the network shown in Figure 7.1, where node G is the host. The S_i are sources of major traffic flows. All nodes are assumed to have some traffic requirements and all communication takes place through the host, G. The goal is to produce routes which have good throughput versus delay characteristics. This gives rise to several conflicting objectives. Min-hop routes minimize the number of times traffic is repeated and hence reduce the total traffic "in the air" as well as delay (for a given hop delay). Routes that separate major traffic requirements onto paths with no overlap except at G will tend to

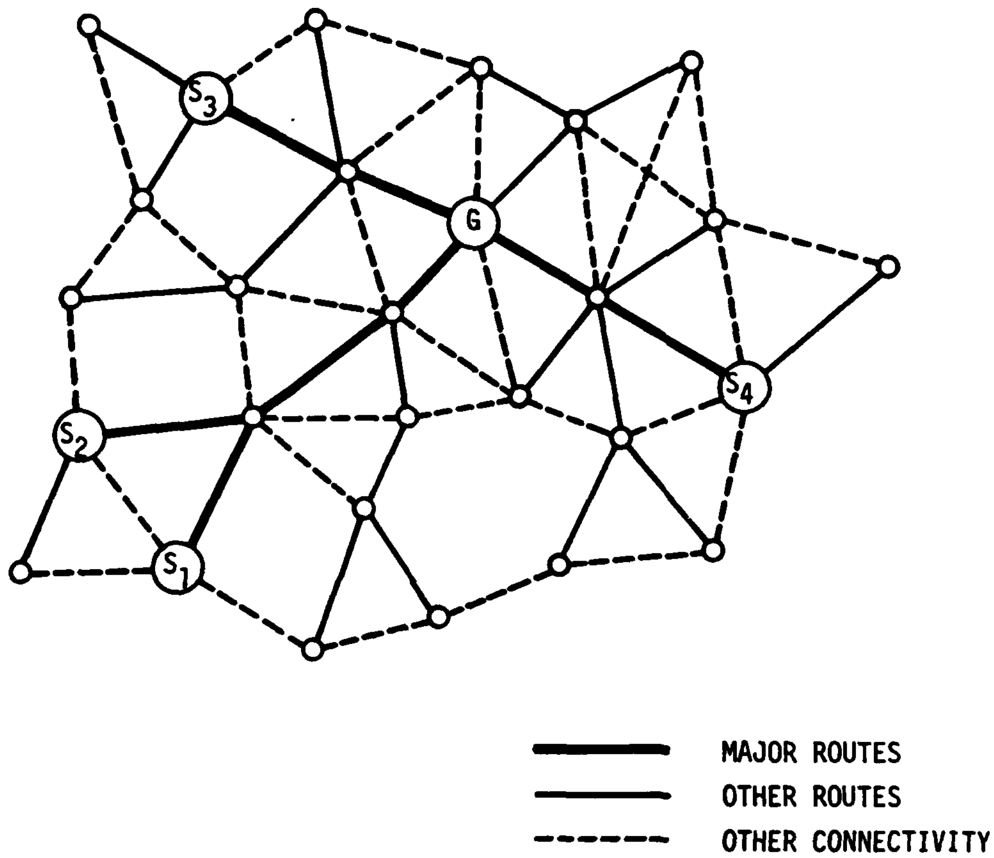


FIGURE 7.1: NETWORK WITH DISTANCE DEPENDENT CONNECTIVITY AND SPARSE TRAFFIC MATRIX

improve throughput by reducing congestion in any local area. Routes which form chains, i.e., in which no three nodes on the route can hear one another, will reduce congestion and interference.

Routes which concentrate traffic to G through a small number of nodes will tend to reduce interference at G since the CSMA is most effective when there are few hidden terminals and separate routes into G (as we described them) would be hidden from one another. The major routes shown in Figure 7.1 as heavy solid lines represent a compromise among these objectives; these routes are not necessarily optimal. They are min-hop and minimally interfering. There are three of them, and they are essentially chains. The existence of such non-interfering, chainlike min-hop routes is a consequence of the distance-dependent nature of the connectivity.

7.3 Routing Procedure

We now describe the proposed routing procedure in detail. The procedure is based upon the principles outlined in the preceeding section and adapted for use in networks with random connectivity. The procedure produces routes with the following characteristics and objectives:

- The routes are min-hop.

- Two nodes one hop (Level I nodes) from G are identified. Ideally, these nodes cannot hear one another nor can they hear any other node one hop from G.

- Ideally, all traffic is divided evenly between these two nodes and enters G through them.

- The two major routes (one through each of these nodes), ideally, are chains and totally disjoint.

The worst case, using this procedure, would be that no two disjoint nodes could be found or that essentially all of the traffic entered through one node. Previous analyses of chains showed that the difference in performance is a factor of two in these two cases. Thus, we have bounded the effect of the procedure.

The procedure described is heuristic for many reasons. First, the network is feasible even in the worst case, as has been shown in the section on throughput analysis. Second, a rigorous treatment of the problem is likely to be time consuming computationally since even the problem of partitioning the nodes into two groups of equal size, in the absence of any other constraints, is NP complete. Finally, the random and unpredictable nature of the connectivity makes execution of the procedure after the actual deployment a necessity and hence, the ability to use a procedure which can be executed quickly with a limited amount of computing power seems highly desirable.

The procedure works in two phases. Phase I identifies likely candidate Level I (the level of a node indicates the number of hops from the host) node pairs to be evaluated in Phase II. For small networks, it may be desirable to evaluate all disjoint pairs since the quality of the solution seems to depend more on the solution of the node pair than upon anything else.

<u>Phase I: Host Routing</u> (Identify likely Level I pairs)

Identify all nodes at Levels I and II by min-hop labeling from the host (level of node equals number of hops that node is from host). Consider all pairs (i,j) of Level I nodes which cannot hear each other directly. (Possibly, restrict (i,j) to those independent of other Level I nodes as well).

For each such i and j:

Let S_i = $\{ K \mid K \in \text{Level II and } i \text{ can hear } K \text{ directly} \}$

S_j = defined analogously.

Compute a figure of merit, f(i,j), for the pair as follows:

$$f(i,j) = \min\{ |S_i - S_j| , |S_j - S_i| \}$$

Do Phase II for one (or more or all) pairs (i,j), considering those with the largest f(i,j) if only a limited number of pairs are to be considered. If only Phase II is to be done for only a single pair (i, j), choose the pair with the largest f(i, j).

Note the selection of the f(i,j) is somewhat arbitrary; for example another criteria is minimum $\{ S_i \cap S_j \}$.

<u>Phase II</u> (Divide traffic between i and j from Phase I)

1. All Level I nodes are assigned to the host.

2. Assign all Level II nodes which can be heard only by I (or j) to i (or j).

2. Starting with the Level II node with the largest traffic, assign nodes which can be heard by both i and j to i or j, whichever is more lightly loaded. Unless these Level II nodes already account for a majority of the overall, traffic, this "load" should simply be the number of nodes.

4. All other Level II nodes, i.e., those that cannot be heard by i or j, starting with the one with the largest traffic should be assigned to the Level I node with the smallest load (traffic).

At this point, all Level I and II nodes are assigned (and have routes).

5. Any node reachable only through paths heard only by i (or j) should be assigned to one of the paths. We work outward by level and descend in traffic magnitude.

6. Nodes reachable through 2 paths, one heard by i or j and the other heard by j only should be assigned to the node with the smaller load.

7. Nodes reachable through paths heard by both i and j (i.e., paths containing a Level II node hear by both i and j) should be assigned to the path with the more lightly loaded Level I node.

8. All other nodes (not reachable through any Level II node assigned to i or j) should be assigned to a Level II node (reachable) which is assigned to the Level I node with the largest traffic. (Ties broken by largest traffic at Level II, etc.)

With this procedure, most nodes and most traffic should be assigned through i and j.

7.4 Computational Experience

The procedure was carried out manually on a version of the C^2 network with random connectivity at 150 dB. The assumed connectivity is given in Table 7.1. The traffic was assumed uniform. A typical solution is given in Figure 7.2. As can be seen, the procedure is reasonably effective, partitioning the traffic fairly well. The fact that it was possible to carry out the procedure manually (in a few minutes) is indicative of its low computational complexity.

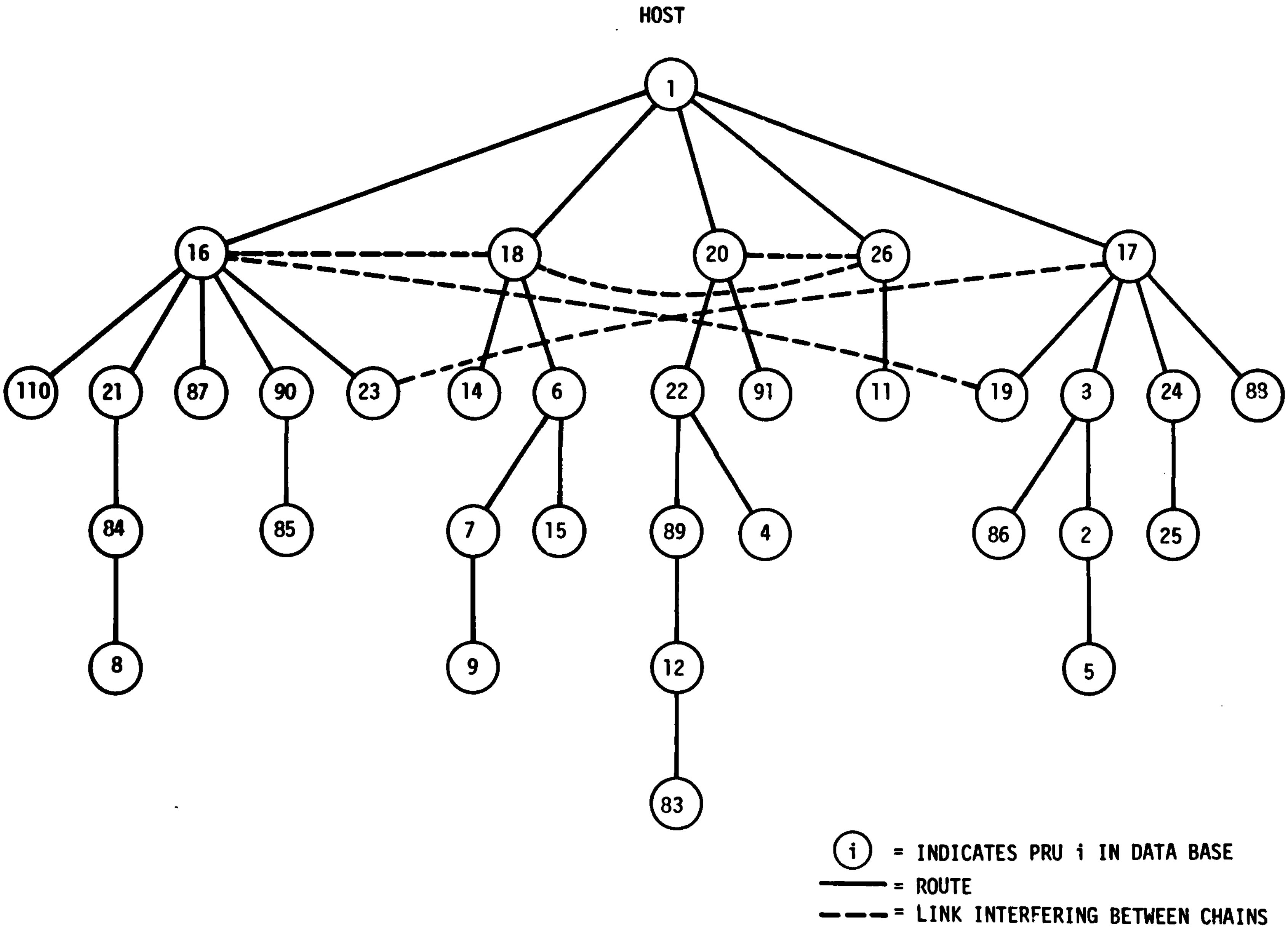


FIGURE 7.2: ROUTE ASSIGNMENT FOR RANDOM LINKS

8. REPEATER LOCATION ALGORITHM

8.1 Introduction

As discussed in Section 2, the configuration problem in its most general form is intended to select an optimal set of repeater locations and routes for all requirements. These requirements include a set of terminal locations, point-to-point traffic requirements, a network performance model (which relates traffic flow to delay), a delay requirement, a coverage requirement, and a set of potential repeater locations (including all of the terminals). The terminals may move, and several snapshots are taken of their locations. Hence, the solution must satisfy all snapshots. Routing patterns and requirements may change from one shapshot to another, but repeater locations (other than terminals acting as repeaters) may not change.

This analysis considers a simpler problem focusing on connectivity issues. We are given a set of terminal locations, $T = \{ t_i \mid i = 1,\ldots,N \}$, a set of potential repeater locations, $R = \{ r_j \mid j = 1,\ldots,M \}$, and a coverage requirement that each *terminal* be able to reach at least K of the selected repeaters. Under the assumption that the repeaters are densely interconnected, this would imply that there are K independent paths between terminals. However, providing a K covering is not sufficient to guarantee K independent paths, but as discussed in NAC's Third Semi-Annual Report, in most cases K independent paths will result. A coverage matrix, $C = \{ C_{ij} \mid i = 1,\ldots, N; j = 1,\ldots, M \}$, indicating which terminals can reach which repeaters is defined such that C_{ij} is 1 if t_i can reach r_j, and is zero otherwise. Thus, in this analysis, we ignore issues of routing, link capacity, details of the link model, and delay and multiple time periods. We focus on the problem of covering the terminals with repeaters.

In our case, the set of potential repeater locations is the set of terminal locations plus some additional fixed repeater locations. It is most desirable to use repeaters which are terminals in the same subnet as the terminals to be covered. It is somewhat less desirable to use repeaters corresponding to terminals in another subnet, and least desirable of all to use fixed repeater locations. The repeater costs (weights) reflect this fact. The methodology developed below is applicable for any of these cases.

A procedure is described below for solving the Set Covering problem (for K = 1) based on a branch and bround algorithm. This procedure was developed before the LOS link

criteria was adopted. With the adoption of the LOS link criteria, there is substantial connectivity in the network. Hence, the repeater location problem is essentially academic. Hence, this procedure was not implemented as part of this contract. However, this procedure was implemented for other NAC contracts and has demonstrated marked efficiency in solving set covering problems.

8.2 Set Covering Problem

The algorithm proposed for solving the repeater location problem is based on a branch and bound procedure as illustrated in the flow chart (Figure 8.1). The algorithm consists of the following basic steps:

- Dominance check (Step 1): A one-time operation to detect redundancy and reduce the size of the problem.
- Branching (Step 2): Defining subproblems with specific repeaters included and excluded from the solution.
- Bounding (Steps 5 and 8): Computing upper and lower bounds corresponding to a subproblem.
- Fathoming (Step 6): Determining whether a subproblem has potential for leading to an optimal solution.

Each of the steps are described in more detail below.

8.2.1 Dominance

Certain repeaters and terminals are redundant and can be eliminated from consideration in the set covering analysis. The following observation enables us to detect redundancy:

Observation 1: If $(C_{ij} = 1) \Longrightarrow (C_{ik} = 1)$, then column j can be eliminated from the problem.

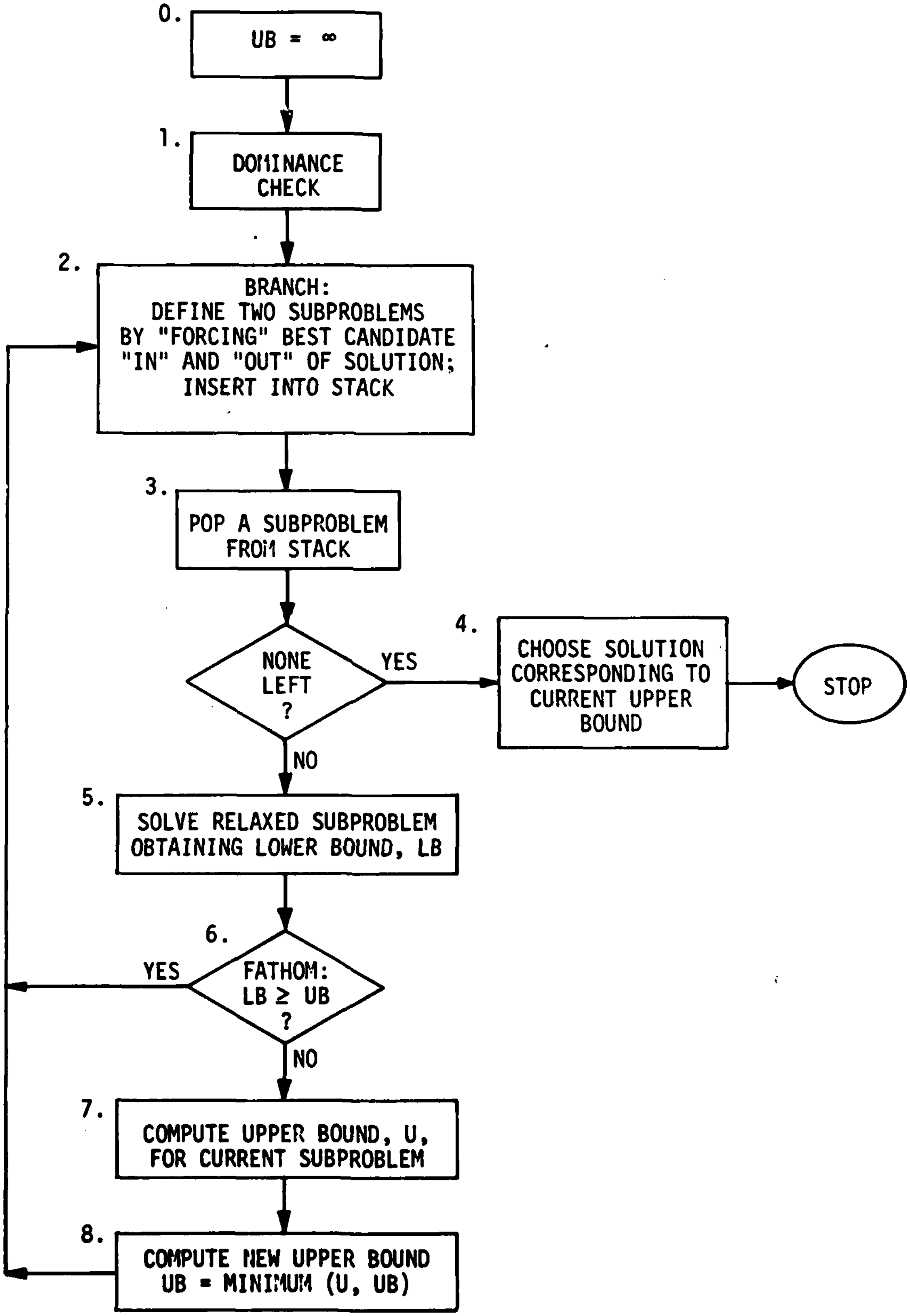


FIGURE 8.1: SET COVERING ALGORITHM

<u>Observation 2:</u> If $(C_{ij} = 1) \Longrightarrow (C_{lj} = 1)$, then row l can be eliminated from the problem.

These observations are, respectively, that repeater k covers all terminals repeater j does, and that terminal l is covered by every repeater which covers terminal i. Clearly, any covering including repeater j could be replaced by a covering using repeater k without degrading the solution. Thus, repeater k dominates repeater j. Similarly, any covering which covers terminal i will also cover terminal l. Thus, terminal i dominates terminal . These dominance relations can be interacted, i.e., after eliminating dominated repeaters and terminals based on the original covering matrix, one may eliminate further repeaters and terminals based on the reduced matrix. In practice, this technique has proven to be very effective, substantially reducing the size of all sample problems (tried by hand with 20 to 50 terminals and repeaters).

8.2.2 Branching

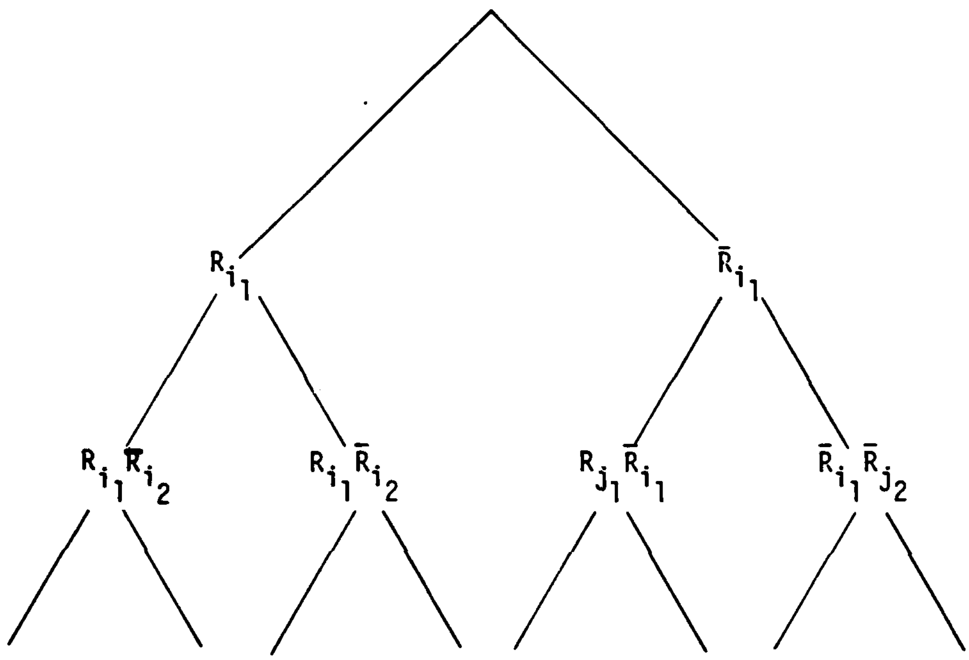
The branching procedure for this algorithm traverses a binary tree as depicted in Figure 8.2. To begin one repeater is selected, say R_{i_1}; then in all solutions descending from the left branch in the tree R_{i_1} is included ("forced in") while in all solutions descending from the right branch R_{i_1} is excluded ("forced out"). Analogously preceeding to the second level, another repeater is "forced in" on the left branch and "forced out" on the right branch. This procedure is then iterated until a node is defined for every possible combination of repeaters.

The criteria used for selecting a new repeater to be forced in or forced out is based on the number of terminals covered by the repeater. The repeater which

- has not yet been "forced," and

- covers the most terminals (that are not already covered by repeaters "forced in" in the current subproblem),

is selected as the repeater to be "forced" in the next level. This is strictly a heuristic criteria and could be replaced by any other arbitrary criteria.



CONVENTION: BAR OVER REPEATER NUMBER MEANS REPEATER FORCED OUT
NO BAR OVER REPEATER NUMBER MEANS REPEATER FORCED IN

FIGURE 8.2: BRANCH AND BOUND TREE

8.2.3 Fathoming

The branching procedure defines a binary tree with nodes corresponding to sets of repeaters "forced in" and "forced out" of the solution. Clearly, one of the nodes in the tree corresponds to an optimal solution to the set covering the problem. If the optimal solution to the set covering problem is not unique, then there are multiple nodes in the tree corresponding to an optimal solution.

The basic strategy of the branch and bound procedure is to traverse the binary tree until an optimal solution is obtained. The major difficulty with this approach is that it is computationally expensive to traverse the entire tree. Hence, it is necessary to devise mechanisms

- to eliminate branches of the tree

- to identify optimal solutions.

The practical mechanism to accomplish this is to compute upper and lower bounds for each subproblem. An upper bound is computed by finding a feasible solution consisting of

- all repeaters "forced in" by the subproblem

- no repeaters "forced out" by the s bproblem

- additional repeaters selected as necessary to meet the coverage constraints.

The procedure for computing the upper bounds described in Section 8.2.4.2. Analogously, a lower bound is computed by a relaxed subproblem; this procedure is described in Section 8.2.4.1.

Thus, given a new subproblem, a relaxed subproblem is solved to obtain a lower bound. If this lower bound exceeds the current upper bound, then there is no possibility of finding a node below the subproblem node with a better solution. Hence, the descendent nodes from the current node need not be explored. In this case, the subproblem is said to fathom; this is illustrated in Step 6 in the flow chart.

However, if the lower bound is less than the upper bound, then there is potential for finding a better solution if the tree below the current node is explored. Hence, branching is performed to define two new subproblems. The algorithm continues until all subproblems have been explored (which either fathom or produce a new pair of subproblems); the optimal solution then is the feasible solution corresponding to the current upper bound.

8.2.4 Relaxed Subproblem

8.2.4.1 Lower Bound

The lower bound is computed by allowing fractions of a repeater to cover a terminal. In Figure 8.3, the Set Covering Problem, P1, and Relaxed Set Covering, P2, are mathematically defined. Given any feasible solution to the P1, we can find a

- feasible solution to P2

- the corresponding solution to P2 will have a smaller objective function value in P2 than the feasible solution in P1.

Hence, the optimal objective value in P2 is a lower bound on the optimal objective value in P1.

Solution of the Relaxed Subproblem consists of first defining weights w_{ij} such that the optimal objective value of P2 is as large as possible. Hence, the lower bound will be as tight as possible. The procedure for doing this is heuristic and is described below. After the weights are selected, an optimal solution is trivially obtained to the relaxed subproblem by choosing for all i:

$$X_{ik} = 1 \text{ for } X_{ik} = \underset{j \in I}{\text{minimum}} \{w_{ij}\}$$

$$X_{ij} = 0 \text{ otherwise.}$$

$$I = \{ \text{ repeater which have not been forced } \}$$

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P1: Set Covering Problem

minimize $z = \sum_j y_j$ $\qquad y_j = 1$ if repeater j is selected

$\qquad = 0$ otherwise.

s.t.

$\sum_j X_{ij} \geq 1$ (all terminals are covered)

$X_{ij} \leq Y_j$ (terminal i can be covered by repeater if and only if repeater j is in the solution)

$X_{ij}, Y_j \in \{0,1\}$

$Y_j = 0$ for all repeaters currently "forced out."

$Y_j = 1$ for all repeaters currently "forced in."

P2: Relaxed Set Covering Problem

minimize $z = \sum_i \sum_{j \in I} W_{ij} X_{ij}$

$\sum_{j \in I} X_{ij} \geq 1$

$X_{ij} \in \{0,1\}$

$I = \{$set of repeaters not forced in or not forced out$\}$

FIGURE 8.3: MATHEMATICAL REPRESENTATION OF SET COVERING PROBLEM AND RELAXED SET COVERING PROBLEM

Lower Bound Procedure

1. Let W_j be the remaining weight associated with repeater j. Initially, $W_j = 1$ for all j. Let S_j be the number of uncovered terminals which can be covered by repeater j. Initial $S_j = \sum_i C_{ij}$ where C_{ij} is the element of the coverage matrix associated with the incidence of terminal i and repeater j. In particular, $C_{ij} = 1$ if repeater j can cover terminal i and 0 otherwise. Set V_i equal to 0 if terminal i is covered by a repeater forced into current solution; one otherwise.

2. If $S_j = 0$ for all j, go to step 7.

3. Find the repeater, K, for which $A = \frac{W_j}{S_j}$ is minimum.

4. Set W_{ij}, the weight associated with the i - j incidence, = A for all uncovered rows covered by repeater K.

5. Update W_j and S_j as follows

   $$W_j = 1 - \sum_i W_{ij}$$

   $$S_j = \sum_i C_{ij} V_i$$

   (Thus, W_j is the remaining weight to be given out for repeater j as S_j is the number of as yet uncovered terminals which can be covered by repeater j.)

6. Return to step 2.

   (At this point, weights have been assigned; find optimal solution.)

7. Select the smallest non-zero elements in each row. This is equivalent to adding the values of W_k found in Step 3.

8. Since the solution must be an integer, we can tighten the bound further by increasing the value in Step 7 to the next highest integer (e.g., if the value was 5.1, return a 6; if the value was 8, return 8).

8.2.4.2 Upper Bound

To obtain the upper bound, a feasible solution is derived from the current solution, which defines constraints on repeaters "forced in" and "forced out." Clearly the objective value associated with a feasible solution is an upper bound, i.e., by definition, an optimal has an objective value less than or equal to the objective value of any feasible solution.

Upper Bound Procedure

This is similar, but not identical, to the lower bounding procedure. A feasible solution is an upper bound. The best feasible solution seen so far is the tightest upper bound.

1. Set $V_i = 1$ for all terminals not covered by forced in repeaters; $V_i = 0$ otherwise; $S_j = \sum_i V_i C_{ij}$.

2. Find $\max_j S_j$. Select this repeater.

3. Set $V_i = 0$ for all terminals covered by the repeater in 2.

4. Set $S_j = \sum_i V_i C_{ij}$.

5. If any $V_i = 1$ for some i, return to Step 2; otherwise, all terminals are covered and repeaters selected (with "forced in" repeaters) comprise a feasible solution.

8.2.5 Enhancements

8.2.5.1 Further Dominance

After certain repeaters are forced in and forced out, the dominance routine may be reexecuted to identify additional redundance in the subproblems.

8.2.5.2 Reevaluation of Lower Bound

When a subproblem is extracted from the stack, the lower bound associated with the farther node of the subproblem node could be compared with the current upper bound. It is possible that the current upper bound asociated may be less than this lower bound, i.e., the upper bound could have been computed since the father subproblem was analyzed. Thus the current subproblem fathoms, i.e., it is no longer desirable to branch from it. Of couse, additional data structures are required to maintain the lower bound.

8.2.5.3 Termination

The algorithm terminates when all subproblems fathom, i.e., it is not worthwhile to perform further branching form the node, or subproblems have no decendants, i.e., if it is not possible to perform branching. This guarantees an optimal solution, but from a practical point of view, it may be desirable to terminate before the optimal solution is obtained. For example, the difference between the current upper bound and smallest lower bound may be so small, that the additional computation (which could be substantial) is not profitable. Thus an alternative termination criteria is stopped when the difference between the current upper bound and the lower bound for all subproblems which have yet to fathom is less than a prespecified threshold.

8.2.5.4 K Cover Problem

The 1-cover algorithm above can be extended to the K cover problem. However,

- The dominance criteria would have to be modified to account for the requirement terminals must be covered by K repeaters.
- The lower bound coverage constraint would be modified so that

$$\sum_j X_{ij} \geq K$$

- The feasible solution in the upper bound would require that terminals be covered by K repeaters.

These modifications are relatively simple conceptually, but the increase in compuational requirements could become substantial. These issues have not yet been addressed in detail.

APPENDIX A

LONGLEY RICE CONNECTIVITY ANALYSIS

A.1 Introduction

This Appendix describes the detailed work done on PR network connectivity using the Longley Rice propagation model. First, a mean attenuation loss model was formulated. In this model, a link exists between two PRU's if and only if the mean attenuation loss between them (calculated by the Longley Rice model) does not exceed the specified loss threshold. A large number of experiments was performed to evaluate network connectivity (using the mean attenuation loss criteria) for loss thresholds of 150 dB, 155 dB, and 160 dB.

The methodology for these experiments and validation of the model are described in Sections A.2 and A.3, respectively. Then the connectivity results are described in Section A.4. These results indicated that the PR networks were sparsely connected and that a substantial number of dedicated repeaters would be required to satisfy the needlines. Specifically, it was determined that even when the threshold is increased to 160 dB, typically well over one-half of the needlines cannot be satisfied without the introduction of dedicated repeaters. If terminals from other subnetworks are allowed to function as repeaters, then the number of needlines that can be satisfied without the introduction of dedicated repeaters significantly increases. However, in the best case for C2, about one-third of the needlines are still not satisfied.

As a result, it was decided to employ a more refined version of the Longley Rice model. This model, referred to as the random Longely Rice model, is described in Section A.5 and has the capability of considering (in a probabilistic fashion) the effects of location variability on attenuation. The results of this model indicated that there was substantially more connectivity than predicted by the mean loss criteria. These results are described in Section A.6. Specifically, for the command control subnetwork with a 150-dB threshold, more than 95% of the PRU's belong to a single connected subset and over 90% of the needlines are satisfied. For both the Field Artillery and Air Defense subnetworks with a 150-dB threshold, there exists only one connected subset; hence, all needlines can be satisfied without the introduction of dedicated repeaters.

Because of the wide disparity in the connectivity predicted by the two models, there was much uncertainty as to how much connectivity there would be if the PR net would be deployed. This led to the decision to employ a LOS criteria in nearly all experiments.

It is noted that the decision not to employ the Longley Rice in determining the links is not meant as a criticism of the model. It is simply the recognition of the reality that a state-of-the-art technology is not able to predict attenuation loss with sufficient accuracy.

A.2 Methodology to Determine Connected Subsets

A.2.1 Network Definition

The Longley Rice Model [6] calculates the attenuation loss between two PRU's, as described in Section 2. If the attenuation loss is less than the specified threshold, a direct link exists. In this manner, the PRU's that can communicate directly can be identified. This then defines a network G(N, A) with a set of vertices, N, comprised of the PRU's, and a set of arcs, A, comprised of the direct links. Sensitivity studies were performed using the threshold value as a parameter. Hence, the network is a function of the threshold value.

A connected subset is a set of at least two PRU's in which each PRU can communicate with every other PRU in the subset by some path. There does not necessarily exist a direct link between each set of PRU's in a subset; however, some path does exist.

A.2.2 Algorithm Description (based on Goodman and Hedetniemi [3])

In order to determine the connected subsets, a network adjacency data structure representation of the direct links in the subnetwork is created. This data structure is made up of two arrays, ADJ(K) and NEXT(K). Let p equal the number of PRU's in the subnetwork. For $1 \leq K \leq p$, ADJ(K) = 0. If J = NEXT(K) for $0 \leq K \leq p$, then ADJ(J) is the first vertex adjacent to vertex K. The next vertex adjacent to K is contained in ADJ (NEXT(J)), and so on.

The connected subsets are computed by a Depth First Search (DFS). Once the adjacency data structure has been defined, the DFS is executed in order to find a tree. In the case being discussed, a tree is a connected subset. This DFS routine is called repeatedly until all the connected subsets in a particular subnetwork are found. In the DFS algorithm the variable V is the current vertex that is being examined. The DFS algorithm proceeds by taking some arbitrary vertex adjacent to V, say vertex W. If vertex W has not yet been visited, the algorithm iteratively finds some adjacent vertex of W. If, however, vertex W has been visited, the algorithm tries some other vertex adjacent to V, always looking for unvisited vertices to visit next. If no unvisited vertices adjacent to V are found, the algorithm backs up to the vertex from which V was visited and tries other adjacent vertices.

In order to remember what the location was when DFS is called, the current values of V and W are stored in a pushdown store. The latest V and W are always at the bottom of the pushdown store. After visiting all the possible vertices of the current vertex and finding that they have been visited, the pushdown store will have the value of the last vertex. Thus it is possible to backtrack and visit its adjacent vertices.

A.2.3 Longley Rice Link Model Application

The input parameters for the Longley Rice link module consist of three types as listed below. Numbers in parentheses below are numerical values for the corresponding parameter.

1. Parameters which are fixed for our studies:

   - The transmission frequency (1,800 MHz)
   - Dielectric constant (15)
   - Ground conductivity (0.005 mho/m)
   - Sea Level Refractivity (310 N units)
   - Antenna Polarization (1, vertical).

The numbers in parentheses above are the numerical values to be used in the studies.

2. PRU parameters:

   - The PR units location coordinates in linear distances (kilometers from NB reference point)
   - Siting parameters
   - Antenna heights.

3. Topography Parameter:

- Terrain Irregularity Parameter (Δh) value.

The fixed parameters were supplied by CORADCOM and are defined by data statements in the Longley Rice subroutine, while the packet radio unit parameters are passed as calling arguments to the Longley Rice subroutine. For terminals, a siting parameter of zero (random) will be used while for repeaters, a siting parameter of 1 (well chosen) will be used. The PR units coordinates and antenna heights are determined from the data base (the Scenario Generator passes these parameters to PRSIM).

The terrain irregularity parameter Δh, an input parameter for the Longley Rice model, characterizes the irregularity of ground topography between two communicating nodes and must be computed each time the Longley Rice subroutine is executed. Since the ground irregularity may vary significantly from one area to another of the network terrain, a matrix of Δh values (Figure A.1) is defined corresponding to a set of cells that cover the area.

The h value used by the link module to determine attenuation loss between any two nodes N_1 and N_2 (Figure A.2) not in the same cell is determined by linear interpolation:

$$h_{N_1,N_2} = \frac{h_1 * \ell_1 + h_2 * \ell_2 + h_3 * \ell_3}{\ell_1 + \ell_2 + \ell_3}$$

This gives a weighted average value of h_{N_1,N_2}. Each cell that line N_1, N_2 passes has its h value weighted by the length ℓ_i that passes through. The weighted sum $\sum_i h_i \ell_i$ is averaged over the total length $\Sigma \ell_i$.

A.3 Validation of Connectivity Results

From the Longley Rice Model, results on attenuation loss in dB versus distance in km for three Δh values have been found. Figure A.3 illustrates attenuation loss vs. range for both Longley Rice results, as well as for published results [4]. The Δh values used in the

(51°N, 9°E) (51°N, $10^{\circ}40'$E)

LATITUDE ↑

214	202	204	295	298	290	351	209	232	228	213	175
155	149	202	304	345	354	305	354	223	396	378	178
160	177	177	247	357	341	197	329	442	263	396	424
178	158	221	198	242	232	271	503	375	273	351	488
142	231	181	272	279	247	314	503	348	280	405	288
240	348	208	305	177	140	402	521	283	282	378	348
164	217	205	222	250	212	308	317	227	226	381	378

(0,o)

($50^{\circ}24'$N, 9°E) LONGITUDE → ($50^{\circ}24'$N, $10^{\circ}40'$E)

NOTES: 1. VALUES OF Δh SHOWN ARE IN METERS.

2. EACH CELL IS 5'8.5" IN LATITUDE AND 8'20" IN LONGITUDE.

FIGURE A.1: Δh VALUES FOR THE FULDA-GAP REGION OF FRG

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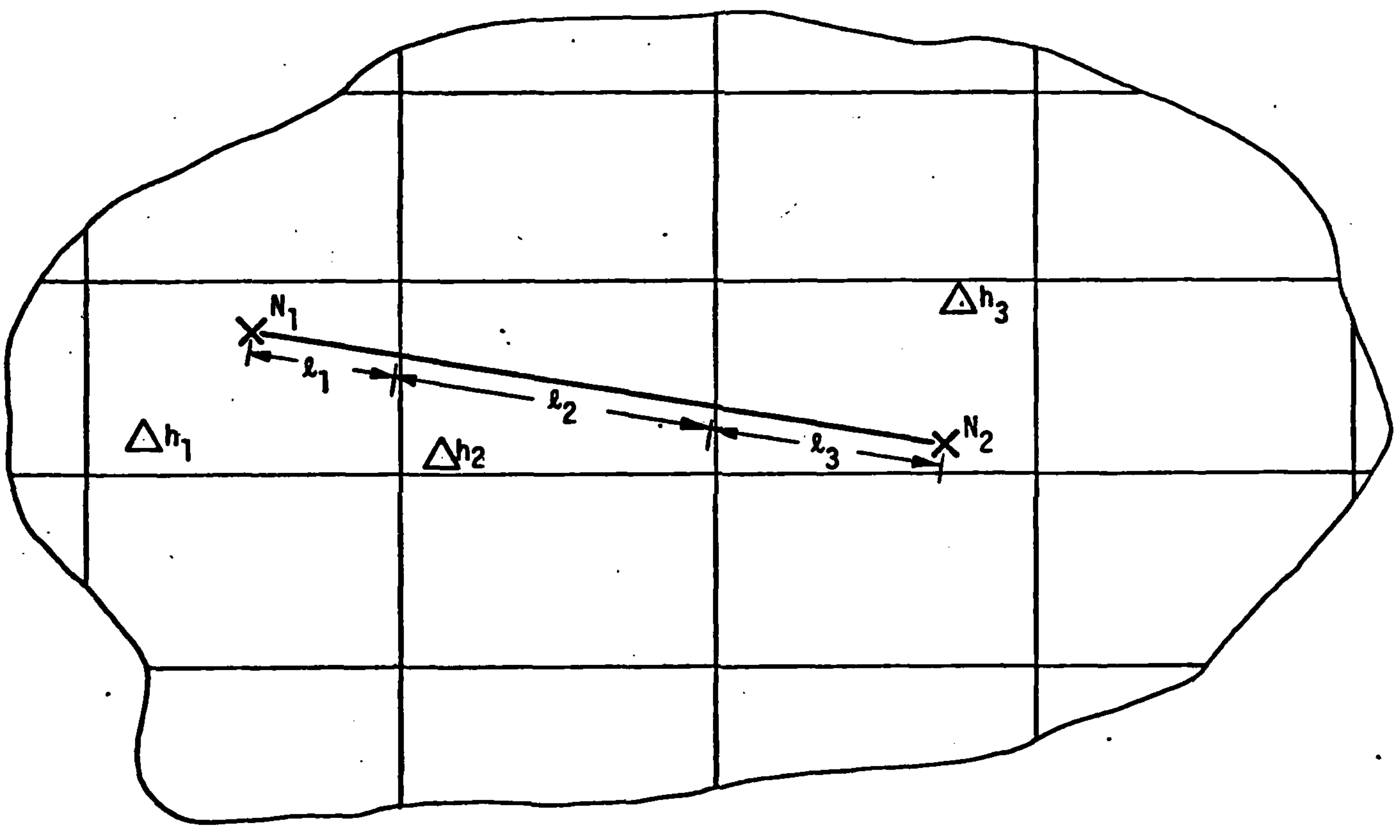

FIGURE A.2: SAMPLE Δh CALCULATION

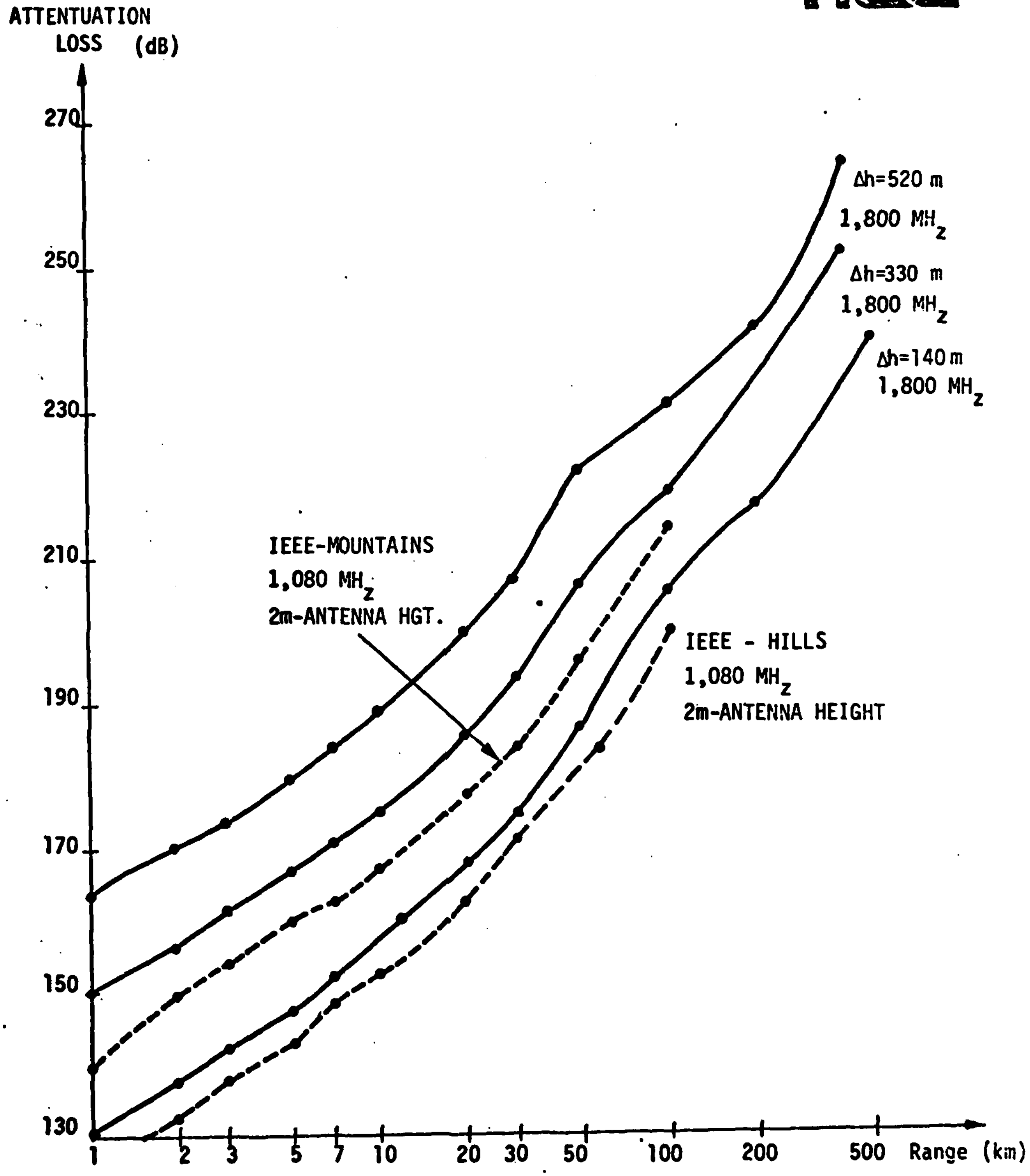

FIGURE A.3: PATH LOSS VS. RANGE

Longley Rice model are the minimum (140m), average (330m), and maximum (520m) values recommended by ECAC for the Fulda Gap terrain being considered for the PR communications system.

The curves indicate that the loss predicted by the Longley Rice Model exceeds the values indicated by the published results. For a low Δ h (140m), the Longley Rice predicted values lie between the published results for hills and mountains; typically, the Longley Rice value is about 5 dB greater than the published results for hills. The results for an average Δh (330m) in the Fulda Gap are about 8 dB greater in attenuation loss than those for mountains. The results for a high Δh (520m) are between 15 and 20 dB higher in attenuation loss than those for mountains. The general trend of the curves is seemingly quite similar to that of the published results.

From Figure A.1, it is found that for a given attenuation loss and a specified range of Δh, the distance between two PRU's must lie within a certain range (in kilometers). This data is summarized in Table A.1, entitled "Range for Communication." For example, consider the first entry in the table which has an attenuation loss of 150 dB, a Δ h value in the interval (140 to 330), and distances between 1 and 6.2 km. This means that for a 150-dB threshold and a Δh of 140m, the maximum range of a PR is 6.2 km. Similarly, for a Δh of 330 m, the maximum range of a PRU is only 1 km. For values of Δ h between 140 and 330 m, interpolation would have to be used. At a threshold of 160 dB and an average Δh value of 330 m, the range of a PR is only 2.7 km. This is considerably less than the 5 to 6 km initially assumed by MITRE in deploying the units. Also, at the maximum value of Δh (520 m), the attenuation loss exceeds the 160-dB threshold at a distance of less than 1 km.

At a frequency of 1,080 MHz, the results have also been found for path loss vs. range. The results found by the Longley Rice Model for a Δh of 140 m are very similar (up to 10 km) to those presented in [4] for hills. As illustrated in Figure A.4, the difference is typically less than 2 dB. The results predicted by the Longley Rice model for a Δ h of 330 m are also very similar those given in [4] for mountains, but the discrepancy is somewhat larger, especially for shorter distance. As shown in Figure A.4 the discrepancy is typically less than 3 dB. The attenuation loss is very much dependent on location. Hence, a substantial part of this discrepancy is likely due to the fact that Longley Rice and the published results are based on data from different locations.

However, after 10 km, the results found by the Longley Rice model differ greatly from those presented in [4].

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TABLE A.1: RANGE FOR COMMUNICATION

Attenuation Loss	Δ h Values	Distance in km
150 dB	$140 < \Delta h < 330$	$1 < dist < 6.2$
150 dB	$330 < \Delta h < 520$	$0 < dist < 1$
155 dB	$140 < \Delta h < 330$	$1.5 < dist < 9.5$
155 dB	$330 < \Delta h < 520$	$0 < dist < 1.5$
160 dB	$140 < \Delta h < 330$	$2.7 < dist < 12.2$
160 dB	$330 < \Delta h < 520$	$0 < dist < 2.7$
175 dB	$140 < \Delta h < 330$	$10 < dist < 30$
175 dB	$330 < \Delta h < 520$	$3.5 < dist < 10$

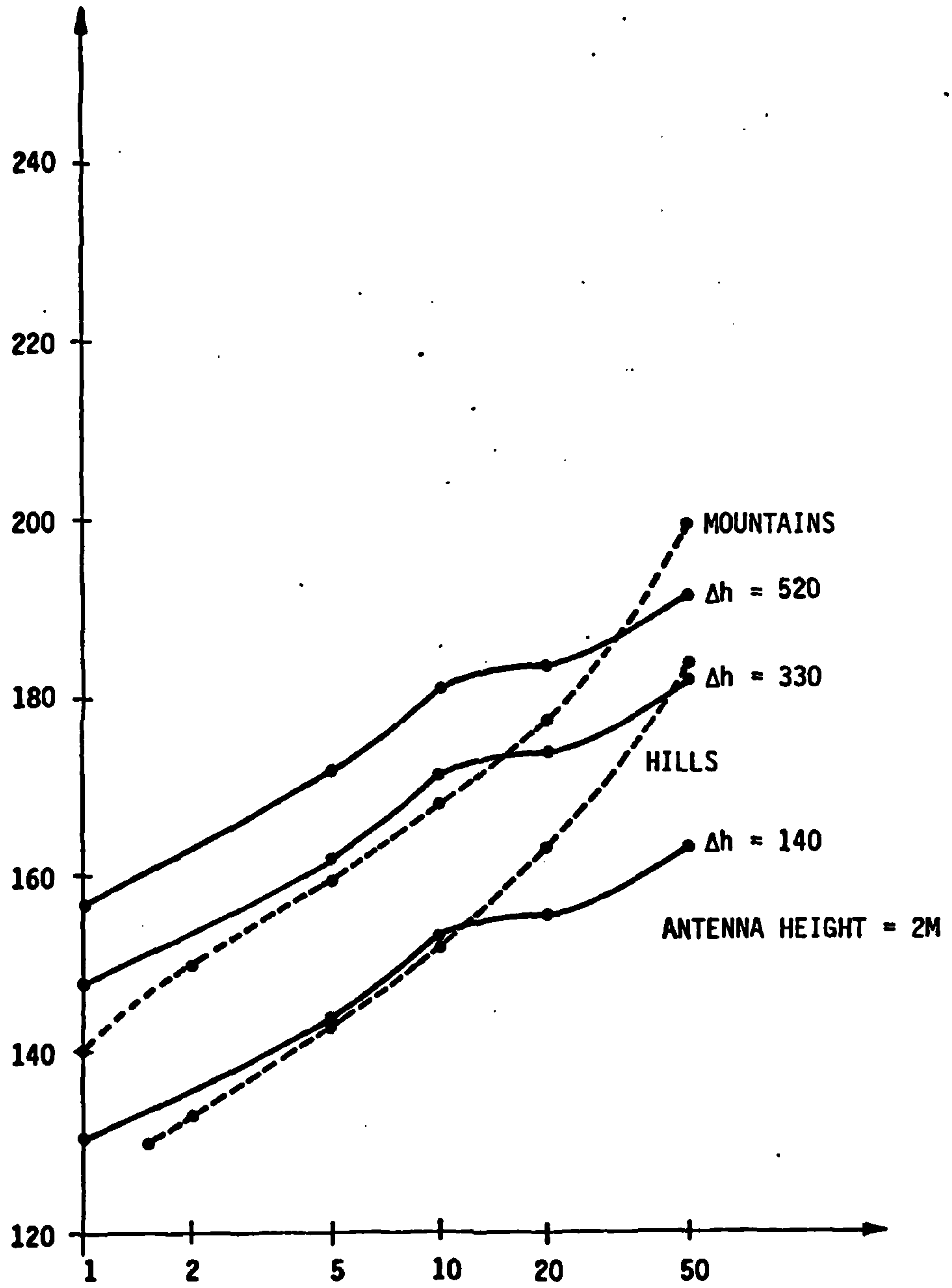

FIGURE A.4: PATH LOSS VS. RANGE AT 1080 MHZ

A.4 Connectivity Results

A.4.1 Command and Control Results

As described in Section 2, the Command and Control subnetwork consists of 36 PRU's and 35 needlines. In the second deployment, three of the units are lost; so in the DL BRAVO deployment, there are only 33 units. In the analysis of the connectivity in the C2 subnetwork, sensitivity studies on the threshold value were performed for each deployment. In each case, threshold values of 150 dB, 155 dB and 160 dB were used.

In general, for all three deployments, there is very little connectivity at 150 dB; increasing the threshold to 160 dB reduces the number of isolated repeaters to approximately one-third of all PRU's, but only about one-third of the 45 needlines are satisfied.

A.4.1.1 Deployment 1

At a threshold of 150 dB, there are three subsets each with two PR units; thus there are 30 isolated PRU's. Only one functional needline of the 45 required is satisfied within the connected subsets. Increasing the threshold to 155 and 160 dB provides significant improvement in connectivity, but there are still a substantial number of isolated PR's and a large number of needlines not satisfied. Specifically, at a threshold of 155 dB, there are three subsets: one has 5 PR units, one has 3 PR units, and one has 4 PR units. In this case there are 24 isolated repeaters, and 6 functional needlines of the 45 required are satisfied. At 160 dB, there are four subsets: one has 12 PR units, two of them have 3 PR units, and one has 2 PR units. Even in this case, there are still 16 isolated repeaters, and only 11 of the 45 needlines are satisfied.

A.4.1.2 DL ALPHA Deployment

In the Defense Line Alpha deployment, there is more connectivity than in the initial deployment, but there are still substantial numbers of isolated PR's and unsatisfied needlines. At a threshold of 150 dB, there are three subsets: one with 7 PR units, one with 3 PR units, and one with 2 PR units. Only 6 functional needlines of the 45 are satisfied, and there are 24 isolated units.

At a threshold of 155 dB, there is a substantial improvement in connectivity resulting in two connected subsets: one with 16 PR units and one with 2 PR units. Fifteen functional needlines are satisfied. At 160 dB, there is a slight improvement in connectivity with three subsets: one has 16 PR units and the other two have 3 PR units. The same 15 functional needlines are satisfied. Thus, nearly two-thirds of the network is connected, but only about one-third of the needlines are satisfied within the connected subsets.

A.4.1.3 DL BRAVO Deployment

In the Defense Line BRAVO deployment, at a threshold of 150 dB, there is one connected subset with 15 PR units and 14 functional needlines are satisfied. This is roughly comparable to the connectivity in the initial deployment at a 160-dB threshold, indicating that the PRU's are more closely grouped in this deployment. Then at 155 dB there is slightly more connectivity; there are two subsets having 16 PR units, and 3 PR units with 15 functional needlines are satisfied. At 160 dB, there are four subsets: one subset has 16 PR units, two have 3 PR units, and one has 2 PR units. Again, 15 functional needlines are satisfied.

A.4.2 Field Artillery Studies

As described in Section 2, the Field Artillery subnetwork consists of 94 PRU's and 177 functional needlines. In the first deployment three of the units are lost, so in DL ALPHA there are 91 PRU's and 174 needlines. In DL ALPHA, 18 more units are lost so that in DL BRAVO there are 73 units and only 156 needlines.

In the connectivity analysis of the Field Artillery subnetwork, sensitivity studies on the threshold value were performed for each deployment. In each case threshold values of 150 dB, 155 dB, and 160 dB were used.

For each deployment there is significant connectivity at the 150-dB threshold, with about 40% of the PR units belonging to some connected subset. However, only a small fraction of the needlines are satisfied (2 to 3% for the initial deployment and DL ALPHA deployment, and 13% for the DL BRAVO deployment). Increasing the threshold to 160 dB causes a substantial increase in connectivity. At this threshold over 80% of the PR units belong to a connected subset, but less than 40% of the needlines are satisfied. Possibly due

to the attrition loss incurred, the connectivity at DL BRAVO at the 160-dB threshold is less than that in the initial deployment. In particular 11% fewer needlines are satisfied in DL BRAVO than in the initial deployment at the 160-dB threshold.

A.4.2.1 Initial Deployment

Of the 94 Field Artillery PRU's at a threshold of 150 dB, there are 13 connected subsets. Of the PRU's, 38% are included in these subsets, while 58 PRU's are isolated. Three of the required functional needlines are satisfied within the connected subsets; this is less than 2% of the 177 required functional needlines. Increasing the threshold to 155 dB provides improvement in connectivity and, when the threshold is raised to 160 dB, nearly all PR units belong to some connected subset. Similarly, as we raise the threshold, there is a significant increase in the number of functional needlines satisfied. Specifically, at a threshold of 155 dB there are still only 13 connected subsets; however, 57% of the PRU's are included in these subsets, while 40 PRU's are still isolated. Twenty-two needlines of the 177 required are satisfied; this is approximately 12½%. At 160 dB there are 14 subsets, yet 93½% of the PRU's are included in these subsets. Only 6 PRU's are still isolated. Although this subnetwork has most PRU's included in a connected subset, only 40% (70 out of 177) needlines are satisfied.

A.4.2.2 DL ALPHA Deployment

For DL ALPHA at 150 dB, there is similar connectivity to the initial deployment. Yet at 160 dB, there is a small decrease in the connectivity relative to the connectivity in the initial deployment. At a threshold of 150 dB, there are 14 connected subsets; 38% of the 91 PRU's are included in these subsets and 56 PRU's are isolated. Only 5 needlines out of 174 are satisfied, just 3%. At 155 dB there are 17 connected subsets with 67% of the PRU's included in them; only 30 PRU's are still isolated. Twenty needlines out of 174 are satisfied, about 11½% of the total. At 160 dB there are only 9 connected subsets, containing 89% of the PRU's in these subsets. Only 10 of the PRU's are isolated. Fifty-nine out of 174 needlines are satisfied, about 34%.

A.4.2.3 DL BRAVO

In DL BRAVO at 150 dB, there is slightly more connectivity than there was in the other two deployments. Of the PRU's, 46% are included in the connected subsets, while in

the other two deployments at this threshold only about 38% of the PRU's were included in the subsets. There are only 9 subsets at 150 dB; out of 76 PRU's, 41 are isolated. Twenty-one of the 156 needlines are satisfied by these subsets, about 13.5%, which is significantly more than the 2% and 3% of the other two deployments. At 155 dB, 67% of the PRU's are included in 12 subsets and 25 PRU's are isolated. Twenty-nine of the 156 needlines are satisfied, about 18%. At 160 dB there is less connectivity than in the other two deployments, only 84% of the PRU's are included in the 7 connected subsets, and 12 PRU's are still isolated. Forty-five of the 156 needlines are satisfied, about 29%. The loss of 21 PRU's from the initial deployment to DL BRAVO has decreased the number of needlines satisfied at 160 dB by about 11%.

A.4.3 Air Defense Artillery

As described in Section 2, the Air Defense Artillery subnetwork consists of 182 PRU's. In the initial deployment, 8 units are lost so that in DL ALPHA there are only 174 PRU's. In DL ALPHA, 23 units are lost, but 5 units, which were held in reserve in the DL ALPHA scenario, are redeployed so that in DL BRAVO there are 156 PRU's. In the analysis of the connectivity of the ADA subnetwork, sensitivity studies on the threshold values were performed for each deployment. In each case threshold values of 150 and 160 dB were used. The results are summarized in the discussion below.

It is interesting to note that in general as the number of PRU's decreases (due to attrition), at a threshold of 150 dB the percentage of connectivity increases. Presumably isolated PRU's close to the battle front are lost. Also, at a threshold of 160 dB, as the number of PRU's decreases, the connectivity also decreases. At the 150-dB threshold, about 60% of the PRU's belong to a connected subset, and when the threshold is increased to 160 dB, about 90% of the PRU's belong to connected subsets. The needlines have yet to be analyzed; this will be done when the needline analysis procedure is automated.

A.4.3.1 Initial Deployment

At a threshold of 150 dB, there are 24 connected subsets made up of 97 PRU's out of a total 182 PRU's; thus about 53% of the PRU's belong to a connected subset, while 85 PRU's are isolated. At a threshold of 160-dB, there are 11 subsets consisting of 171 PRU's. One of these subsets consists of 108 PRU's. Thus 94% of the PRU's belong to some connected subset and 59% belong to the same connected subset.

A.4.3.2 DL ALPHA Deployment

At a threshold of 150 dB, there are 30 subsets of 92 PRU's out of 174. Sixty-two PRU's are isolated. At a threshold of 160 dB, there are 15 subsets of 157 PRU's, about 90% connectivity. One of the subsets consists of 50 PRU's, and there are only 17 isolated PRU's.

A.4.3.3 DL BRAVO Deployment

At a threshold of 150 dB, there are 107 PRU's out of 156 in 17 subsets; this is about 68% connectivity. One of the subsets consists of 39 PRU's and there are 49 isolated PRUs. At 160 dB, there are 138 PRU's in 9 connected subsets. One subset has 50 PRU's (32% of all PRU's) and another has 58 PRU's (37% of all PRU's). Thus approximately 88% of all PRU's belong to a connected subset and only 18 PRU's are isolated.

A.4.4 Whole Network

The entire network (consisting of the three subnetworks Command and Control, Field Artillery, and Air Defense Artillery) contains a total of 297 PRU's in the initial deployment. Eleven PRU's are lost in this deployment so that in DL ALPHA there are 286 PRU's. In DL ALPHA, 42 PRU's are lost, and 5 are held in reserve and then redeployed in DL BRAVO so that there is a total of 249 PRU's in DL BRAVO.

In the connectivity analysis of the network, sensitivity studies on the threshold values were performed for each deployment with threshold values of 150 and 160dB. At both 150 and 160 dB, there were substantial improvements in connectivity, but a large number of needlines were not satisfied. It was determined for both the initial deployment and the DL ALPHA deployment that over 200 PRU's belong to the same connected subset for a 160-dBthreshold, and about 97% of the PRU's belong to some connected subset. The complete set of needlines were not analyzed, but for the initial deployment of C2, it was found that 18 of 45 needlines were satisfied with the introduction of repeaters from other subnets (an increase of 7 needlines). For the DL ALPHA deployment, there was an increase (from 15 to 34) in the number of needlines being satisfied. However, in DL BRAVO at 160 dB, the improvements in connectivity were not as significant. In this case only 99 terminals were contained in the largest subset. More detailed results are presented below.

A.4.4.1 Initial Deployment

At a threshold of 150 dB, 240 PRU's out of 297 are included in 44 subsets. This means that about 81% are included in some connected subset and that 37 PRU's are isolated. At 160 dB, 290 PRU's are included in 12 subsets; thus about 97.5% of the PRU's are contained in some connected subset. One of these subsets consists of 205 PRU's, while another has 43 PRU's. Only 7 PRU's are isolated. Thus when the entire network is considered at 160 dB, substantial network connectivity exists.

For the Command and Control network at a threshold of 150 dB, using PRU's from other subnetworks as repeaters, there are 7 PRU's in 2 subsets, but 29 PRU's are isolated. Without the repeaters, there are 6 PRU's in 3 subsets. Four out of 45 needlines are satisfied with the use of repeaters, but without them only 1 needline is satisfied. At 160 dB with the use of repeaters, 29 PRU's are included in 3 subsets and 18 out of 45 needlines are satisfied. Only 7 PRU's are isolated. Without the use of repeaters, 20 PRU's are included in 4 subsets and only 11 of the 45 needlines are satisfied. Thus even with this substantial improvement in connectivity, a substantial number of dedicated repeaters may be required to satisfy the needlines.

A.4.4.2 DL ALPHA Deployment

At a threshold of 150 dB, 219 out of a possible 286 PRU's are included in 62 connected subsets; this is about 76% of the PRU's with 47 PRU's isolated. At 160 dB, 278 PRU's are included in 9 subsets. One of these subsets has 239 PRU's in it and only 8 PRU's are isolated. Hence, in this deployment, there is also substantial connectivity at 160 dB.

For C2 at a threshold of 150 dB, with PRU's in other subnetworks acting as repeaters, 13 PRU's are included in 2 subsets and 23 PRU's are isolated. Ten out of the 45 needlines are satisfied. Without the use of repeaters, there are 12 PRU's in 3 subsets and only 6 out of the 45 needlines are satisfied. At 160 dB with the use of repeaters, there are 2 subsets, one with 28 PRU's and one with 3 PRU's. Only 5 PRU's are isolated and 34 out of 45 needlines are satisfied. Without the use of repeaters, there are three subsets consisting of 22 PRU's, and only 15 of the 45 needlines are satisfied. Thus, in this case, using terminals from other subnetworks as repeaters significantly increases the number of needlines that can be satisfied without the introduction of dedicated repeaters.

A.4.4.3 DL BRAVO Deployment

At 150 dB, 198 PRU's out of a possible 249 are included in 34 subsets, about 80%. One of these subsets has 63 PRU's and 51 PRU's are isolated. At 160 dB, 240 PRU's are included in 14 subsets and only 9 PRU's are isolated. However, only 99 PRU's are contained in the largest connected subset, as opposed to over 200 in both of the previous deployments.

For the C2 subnetwork at a threshold of 150 dB, with terminals from other subnetworks acting as repeaters, there are 2 subsets: one with 15 PRU's and one with 2 PRU's. Out of the 33 PRU's, 16 PRU's are isolated and 14 needlines out of 42 are satisfied. Without the use of repeaters, there is one subset of 15 PRU's and the same 14 needlines are satisfied. At 160 dB with repeaters, there are three subsets of 25 PRU's, so that only 8 PRU's are isolated. Sixteen out of 42 needlines are satisfied by these subsets. Without the use of repeaters, there are 24 PRU's in 4 subsets and 15 needlines are satisfied. In this case the use of terminals from other subnetworks (functioning as repeaters) only minimally increases the number of needlines satisfied.

A.5 Methodology for Random Longley Rice Model

One of the deficiencies of the Longley Rice model is that it incorporates all the topographic information into a single parameter, the interdecile range (Δh). Hence, there are salient characteristics of the terrain, e.g., foliage, that are not explicitly captured by the Longley Rice model. As a result, the measured attenuation of two pairs of points with the same interdecile range can be markedly different. It has been empirically observed [3] that this location variability is normally distributed. Typically, the standard deviation of the distribution is approximately 20 dB. This standard deviation is quite large compared to the assumed connectivity attenuation loss threshold of 150 dB. Hence, the random algorithm for determining connectivity that accounts for this location variability has been applied to determine connectivity.

As indicated above, the analysis of attenuation-loss measurement data has shown that the attenuation loss variation due to location is normally distributed about the mean attenuation loss predicted by the Longley Rice model. An expression to find the standard deviation has been developed by Dr. Longley [7]:

$$\sigma_L = 6 + 0.55(\Delta h/\lambda)^{1/2} - 0.004(\Delta h/\lambda)\ \mathrm{dB} \tag{1}$$

for h/λ 4,700, or

$$\sigma_L = 24.9 \text{ dB}$$

for $\Delta h/\lambda <$ 4,700, where Δh is the interdecile range of the pair of PRU's and the wavelength $\lambda = 0.167$ m.

Given the mean attenuation loss from the Longley Rice model and the standard deviation, a spread of three standard deviations about the average attenuation loss is found. Then, using a random number generator, an attenuation loss value from the normal distribution within the plus/minus 3 standard deviations is generated.

This value for the attenuated loss is compared to the specified threshold, assumed to be 150 dB in these experiments. If the attenuation loss is less than the specified threshold, a direct link exists. In this manner, the PRU's that can communicate are identified. This then defines a network G(N,A) with a set of vertices, N, comprised of the PRU's and a set of arcs, A, comprised of the direct links. The Depth First Search described above is then applied to find the connected subsets. Given the connected subsets and the needlines in the traffic data base, a computer program was written to determine automatically which of the needlines were satisfied within each connected subset.

To generate a random attenuation loss within the plus/minus 3 standard deviation, Composition Method [5] is applied to compute the random variable. Define S as a random variable such that:

$$S = Y_1 + Y_2 + \ldots + Y_n,$$

where $Y_1, Y_2, \ldots, Y_n$ are independent samples of the uniform variates is between 0 and 1, which are generated based on some random seed. Then, for large n, the variable S is approximately normally distributed with mean n/2 and variance n/12. Then, the variable X defined by:

$$X = \frac{S - \left(\frac{n}{2}\right)\sigma}{\sqrt{n/12}} + \mu$$

approximates the normal variable with mean and variance σ^2. by choosing n = 12, the square root is eliminated. Note the value of n truncates the distribution at $\pm 6\sigma$ limits.

Thus, X is only an approximation to a variate with a standard normal distribution within [3]. Subsequent experiments were run ignoring variates beyond [3] and similar results were obtained.

To apply the above results, the standard deviation is obtained from Equation (1), which is an expression developed by Dr. Longley for the standard deviation of the attenuation loss. The mean μ is the mean attenuation loss obtained from the Longley Rice model.

A.6 Results

In this section, the results of the connectivity experiments are described. A needline defines communication requirement between two PRU's. If the communication requirement is in only one direction (A to B or B to A), then the needline is referred to as a half-duplex needline. If the requirement is in both directions (A to B and B to A), the needline is referred to as a full duplex needline.

In comparing the results found by the random method to those found using a mean attenuation loss, there is a substantial increase in the connectivity. Even when the threshold is raised to 160 dB, the connectivity is much less than that found with the random method with a threshold of 150 dB.

A.6.1 Command and Control Results

With the random connectivity algorithm at a threshold of 150 dB, there is one subset of 34 oF the 36 PRU's in the initial deployment. All of the 45 needlines are full-duplex and 41 are satisfied. At this threshold for this subnetwork and this deployment, several analyses have been made for different random values. Each time, the same number of PRU's belonged to the connected subset, though they were not the same PRU's. This results from the fact that the direct links are not the same for each run.

At 150 dB, using the mean attenuation loss algorithm to find connectivity, there are only three subsets of 2 PRU's each, and only one needline of 45 is satisfied. By increasing the threshold to 160 dB for the initial deployment, there are four subsets: one has 12 PRU's, two have 3 PRU's, and one has 2 PRU's. In this case, 16 PRU's are isolated and only 11 needlines are satisfied. Even by increasing the threshold to 160 dB, the connectivity is still much less that that found when using the random method. Many more repeaters are necessary in order to achieve the proper connectivity. The Main CP (PRU 1 in the data

base), which is the PRU with the heaviest traffic, has very few of its needlines satisfied within the connected subset. For example, the three Brigades (2,3,4) are all about 20 to 25 km away, and so would need about 4 to 5 repeaters to be able to communicate. The Cavalry Squad (15) is at least 40 to 50 km away from the Main CP(1) and also has a requirement; in this case, it could use some terminals as repeaters, but would probably still need about 8 repeaters. The Field Artillery (70) cannot communicate with any of the necessary PRU's. The closest of the PRU's which has a requirement to the Field Artillery (87) is about 10 to 15 km away and would need 2 to 3 repeaters. Of couse, the required number of repeaters depends on the detailed topography and terminal repeater siting.

The Division Artillery (26) can communicate with the Main CP(1) and with one other of the PRU's with which it needs to communicate. But, all the other PRU's it needs to communicate with are scattered across the terrain. The Division Support Command (20) is probably the only PRU that has all its needlines satisfied. All those that communicate with it lie in the same area.

When terminals in the two other subnetworks are used as repeaters (both at 150 and 160 dB), there is quite a bit more connectivity. However, a large number of the C2 needlies are still not satisfied. It was determined for both the initial deployment and the DL ALPHA deployment that over 200 PRU's out of 297 PRU's belong to the same connected subset for a 160 dB threshold. About 97% of the PRU's belong to the same connected subset. For the initial C2 deployment, 18 out of the 45 needlines were satisfied with the introduction of repeaters (an increase of 7 needlines). This is still much less than the number of needlines satisfied by the random method.

Similar results have been found for the other deployments of the C2 subnetwork. Therefore, the results of DL ALPHA and DL BRAVO are not stated in as much detail. At DL ALPHA, using the random algorithm, there is one subset of 35 PRU's out of 36, and 43 out of a possible 45 needlines are satisfied. Using the mean attenuation loss value, there are three subsets of 7, 3, and 2 PRU's, and only six functional needlines of the 45 required are satisfied.

In summary, for all three deployments, the results obtained by the random method show substantially better connectivity than those found by mean attenuation loss.

A.6.2 Field Artillery Results

For the initial deployment at a threshold of 150 dB, using the random method, 94 out of a possible 94 PRU's are in one connected subset; therefore, all 177 needlines are satisfied.

For the mean attenuation loss algorithm, 45 PRU's are included in 13 subsets. This is only about 38% of the PRU's, and only 3 needlines are satisfied. In comparison to 150 dB, this is a substantial increase, but it is still much less than with the use of the random method.

For DL ALPHA, once again using the random method, there is 100% connectivity; 91 of the 91 PRU's are in one subset and all 174 needlines are satisfied. For mean attenuation loss, 35 PRU's are included in 14 connected subsets and only 5 needlines are satisfied. For DL BRAVO, there is also 100% connectivity using the mean attenuation algorithm; all 73 PRU's are part of the same subset and all 156 needlines are satisfied. For the mean attenuation loss, there are 35 PR units in 9 subsets. The connectivity is this deployment is a little better than for the other deployments, but still only 46% of the PRU's are included. At 160 dB, there are 7 subsets of 61 PRU's and 45 needlines are satisfied.

It is quite obvious that the use of the random method demonstrates much greater connectivity.

A.6.3 Air Defense Artillery

This subset consists of 182 PRU's. By using the random method for the initial deployment, all 182 PRU's in the ADA subnetwork belong to one subset and all needlines are satisfied. for the mean attenuation loss criteria, there are 24 subsets made up of 97 of the 182 PRU's. At 160 dB, there are 11 subsets consisting of 171 PRU's. This is quite good; however, since they are dispersed among separate subsets, the needlines satisfied by this method are still not as many as with the random method.

APPENDIX B

FEASIBILITY OF MOBILE SUBSCRIBER ENTRY SYSTEM
AND
PACKET RADIO SYSTEM TO SUPPORT ARMY DATA NEEDLINES

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FEASIBILITY OF MOBILE SUBSCRIBER ENTRY SYSTEM AND PACKET RADIO SYSTEM TO SUPPORT ARMY DATA NEED LINES

MSE/PR/1

THE PROBLEM

- GIVEN: ARMY DATA NEED LINES

  MSE CONCEPTS

  PACKET RADIO SYSTEM CONCEPTS

- DETERMINE:

  - CAN THE MSE SYSTEM SUPPORT THE DATA NEED LINES?
  - CAN A PACKET RADIO SYSTEM SUPPORT THE DATA NEED LINES?
  - HOW MUCH NARROW BAND VOICE CAN BE CARRIED BY A PACKET RADIO SYSTEM (AT 2.4KBPS OR 1.2KBPS) AND STILL SUPPORT THE DATA NEED LINES

- CONSTRAINTS:

  - ONE MONTH TIME FRAME
  - DATA NEED LINES NOT FULLY SUITABLE TO INVESTIGATE BROADCAST/BUFFERED SYSTEMS
  - MSE IN CONCEPT STAGE AND NOT FULLY DEFINED
  - MSE VOICE REQUIREMENTS LIMITED IN DETAIL

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MSE DESCRIPTION

- RADIOTELEPHONE SYSTEM:
  - MOBILITY OF RADIO
  - ADDRESSABILITY OF TELEPHONE
- BASIC COMPONENTS:
  - TERMINAL (MST)
  - CENTRAL (MSC)
  - ACCESS UNIT (AU)

MOBILE SUBSCRIBER TERMINAL (MST)

- USER INSTRUMENT
- VOICE - DIALUP OR DAS
- DATA INTERFACE - DIALUP OR DAS
- PRIME MOVER
  - JEEP
  - SHELTER
  - COMMAND TRACK
  - ARMY AIRCRAFT
- FULLY COMSEC SECURED

MOBILE SUBSCRIBER CENTRAL (MSC)

- RANGE EXTENSION THRU RETRANSMISSION
- INTERFACE WITH CORPS SYSTEM
- COMSEC KEY DISTRIBUTION
- SHELTER MOUNTED
- SET UP / TEAR DOWN - 30 MINUTES

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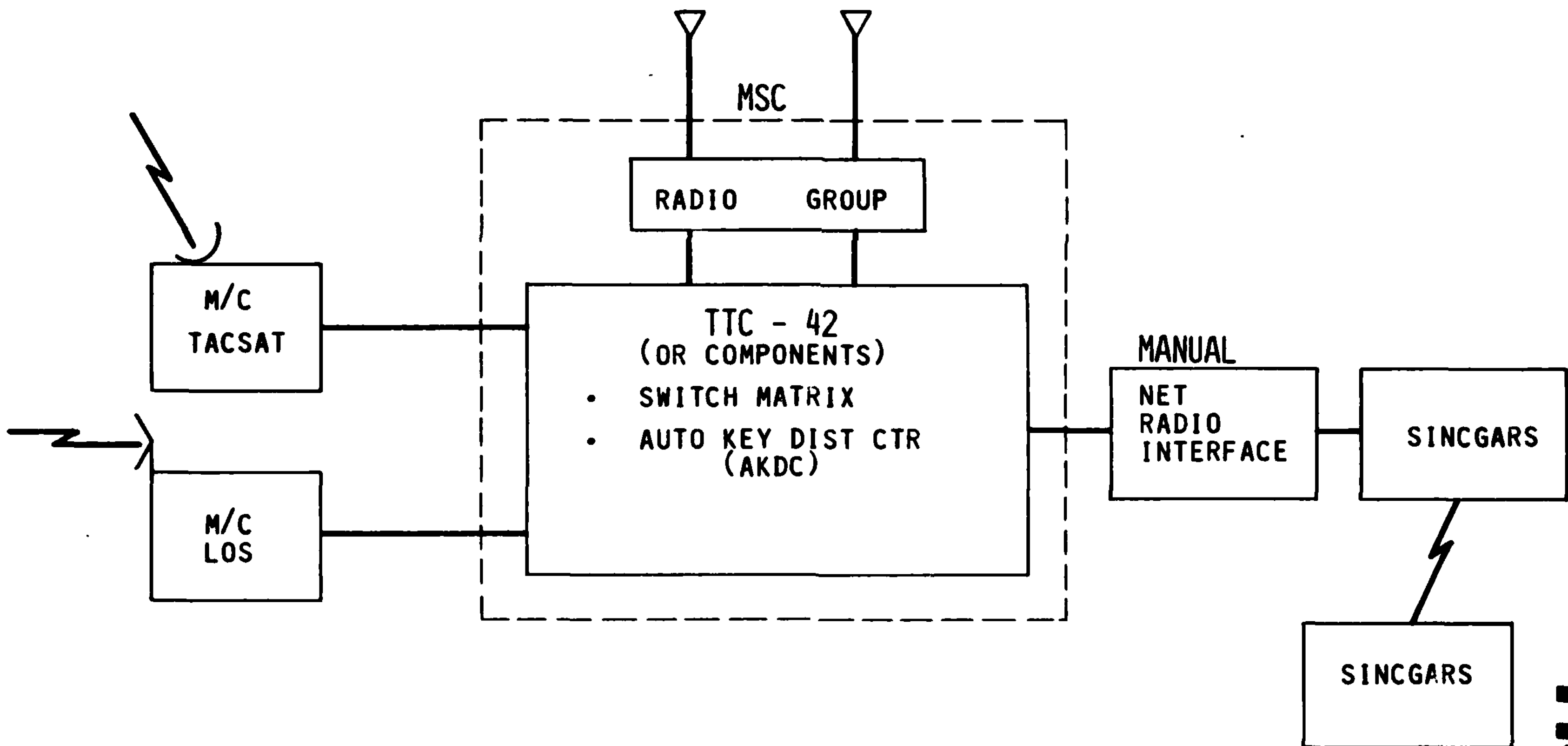
ACCESS UNIT (AU)

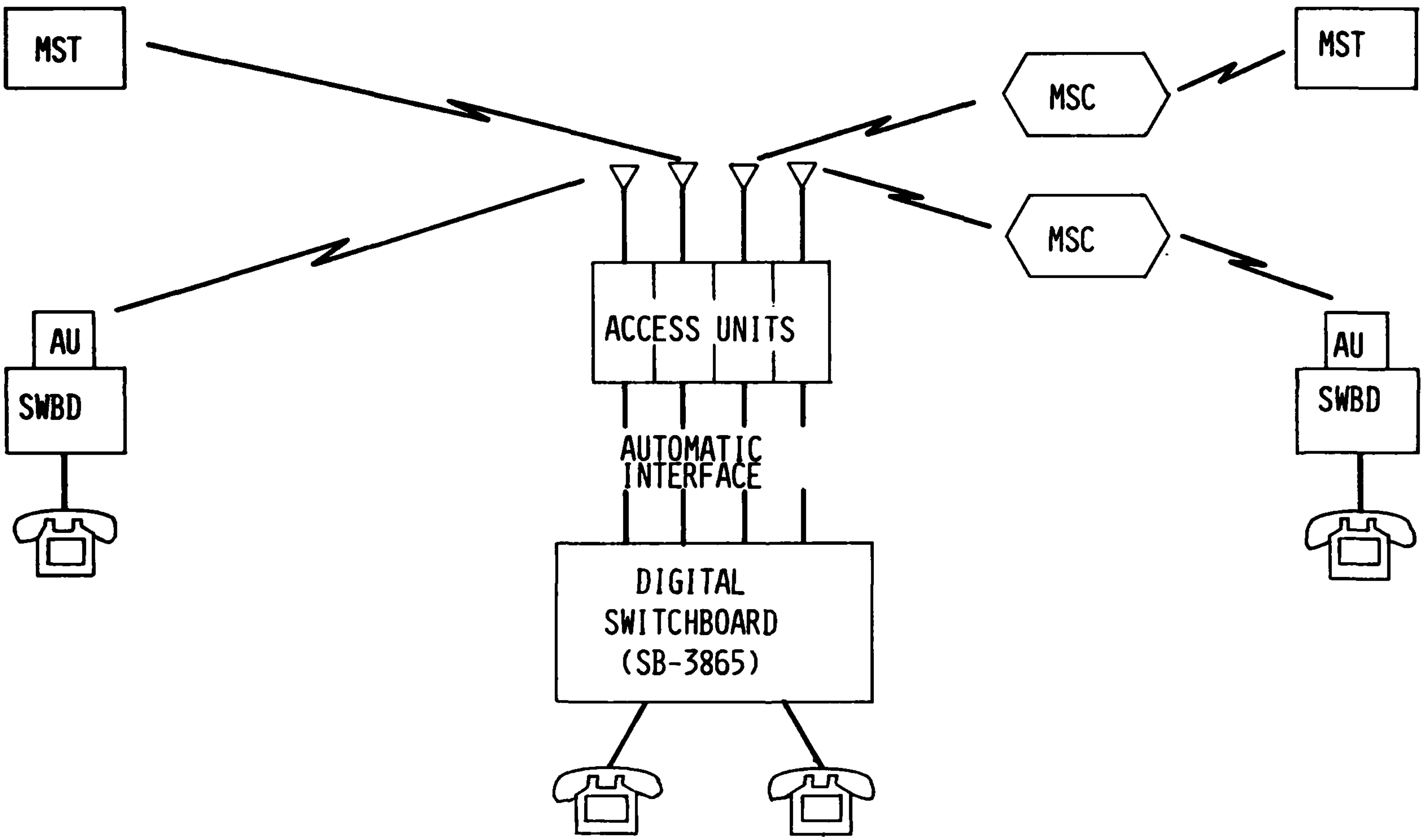
- INTERFACE FOR TEL CALLS INTO MSE SYSTEM
- LOCATED WITH TEL SWBD
- COMSEC SECURED

<u>MOBILE SUBSCRIBER CENTRAL</u>

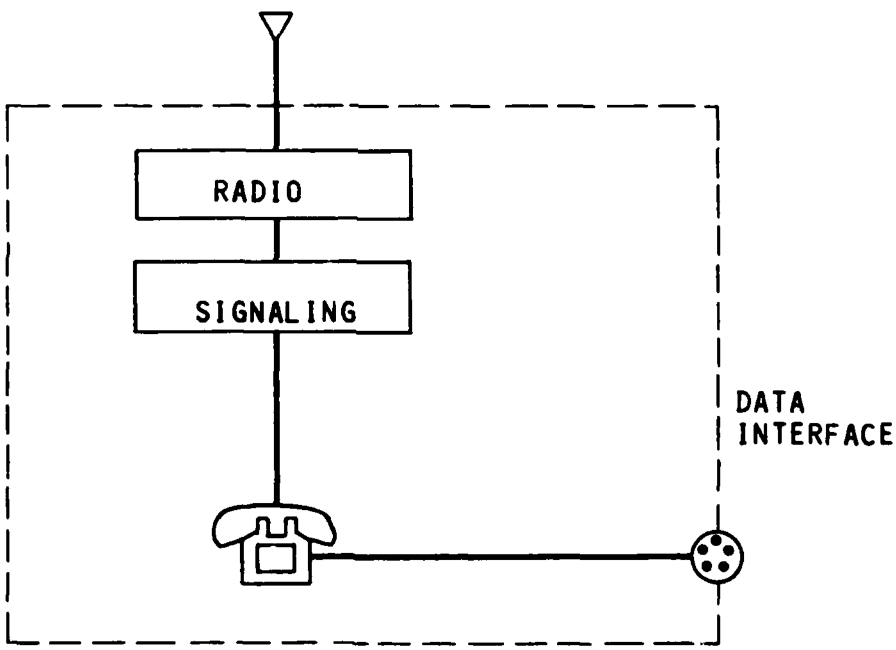


<u>ACCESS UNIT</u>

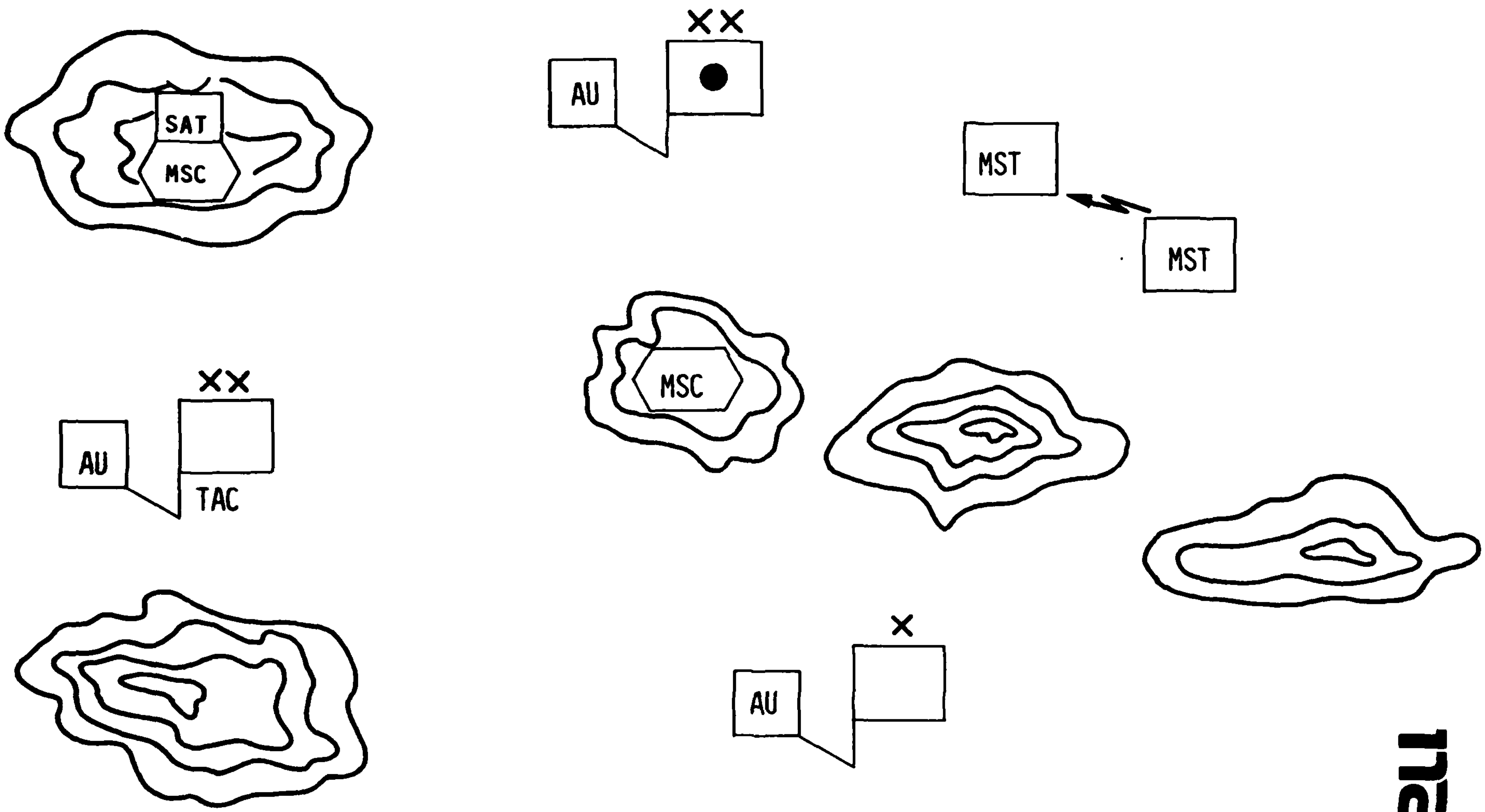
<u>DIGITAL SWBD</u>



MOBILE SUBSCRIBER TERMINAL



MSE OPERATIONAL CONCEPT



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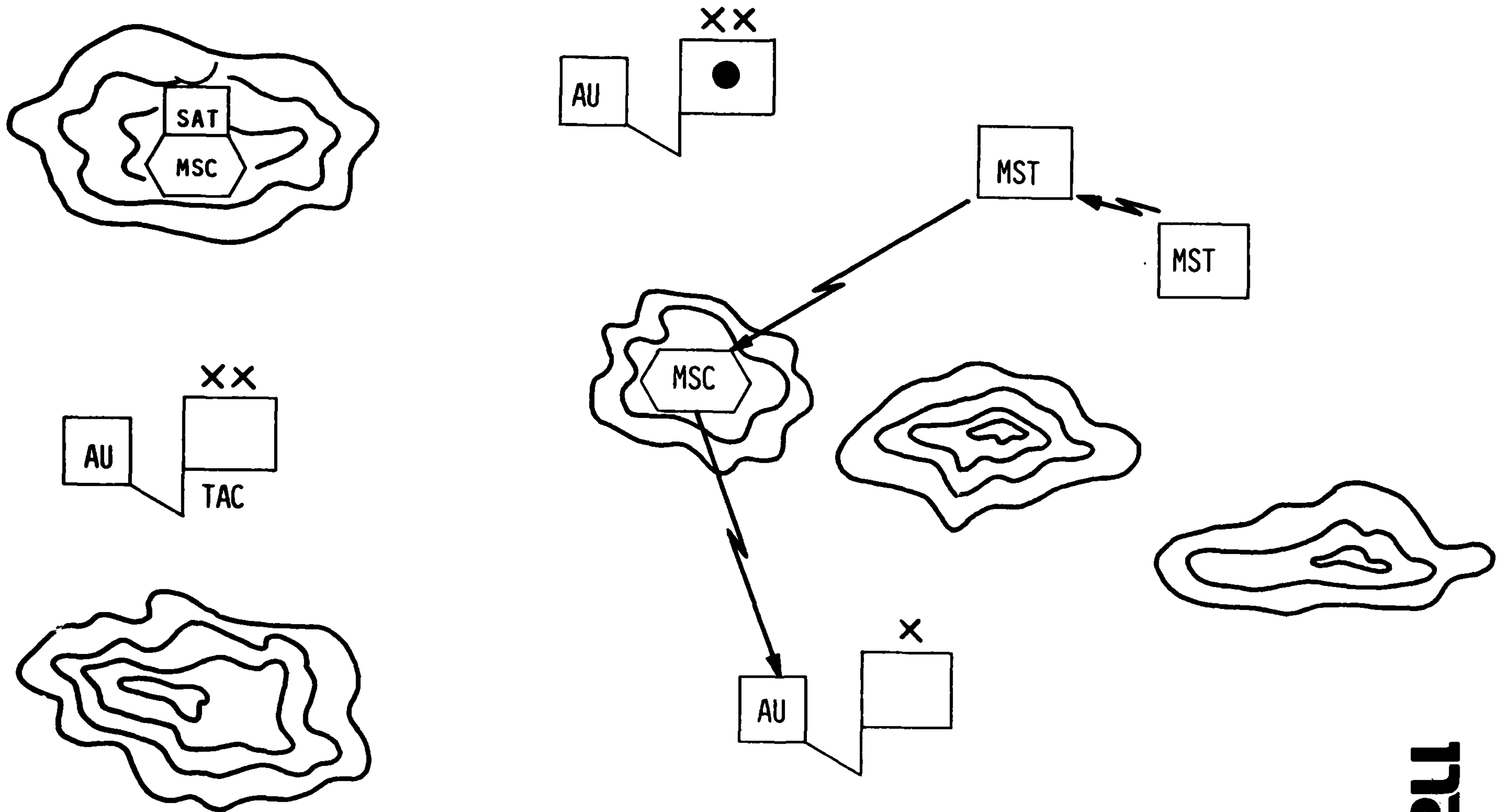

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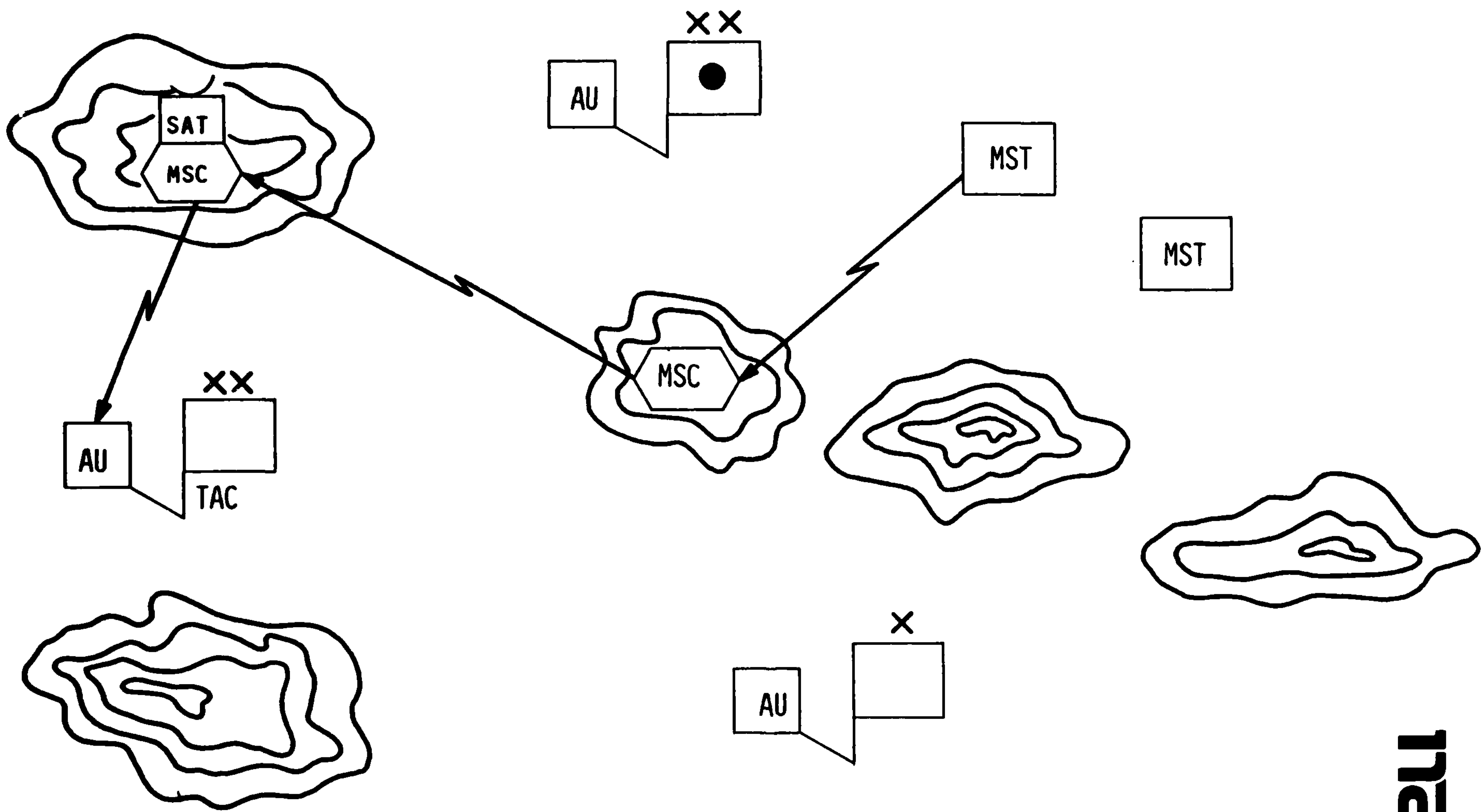
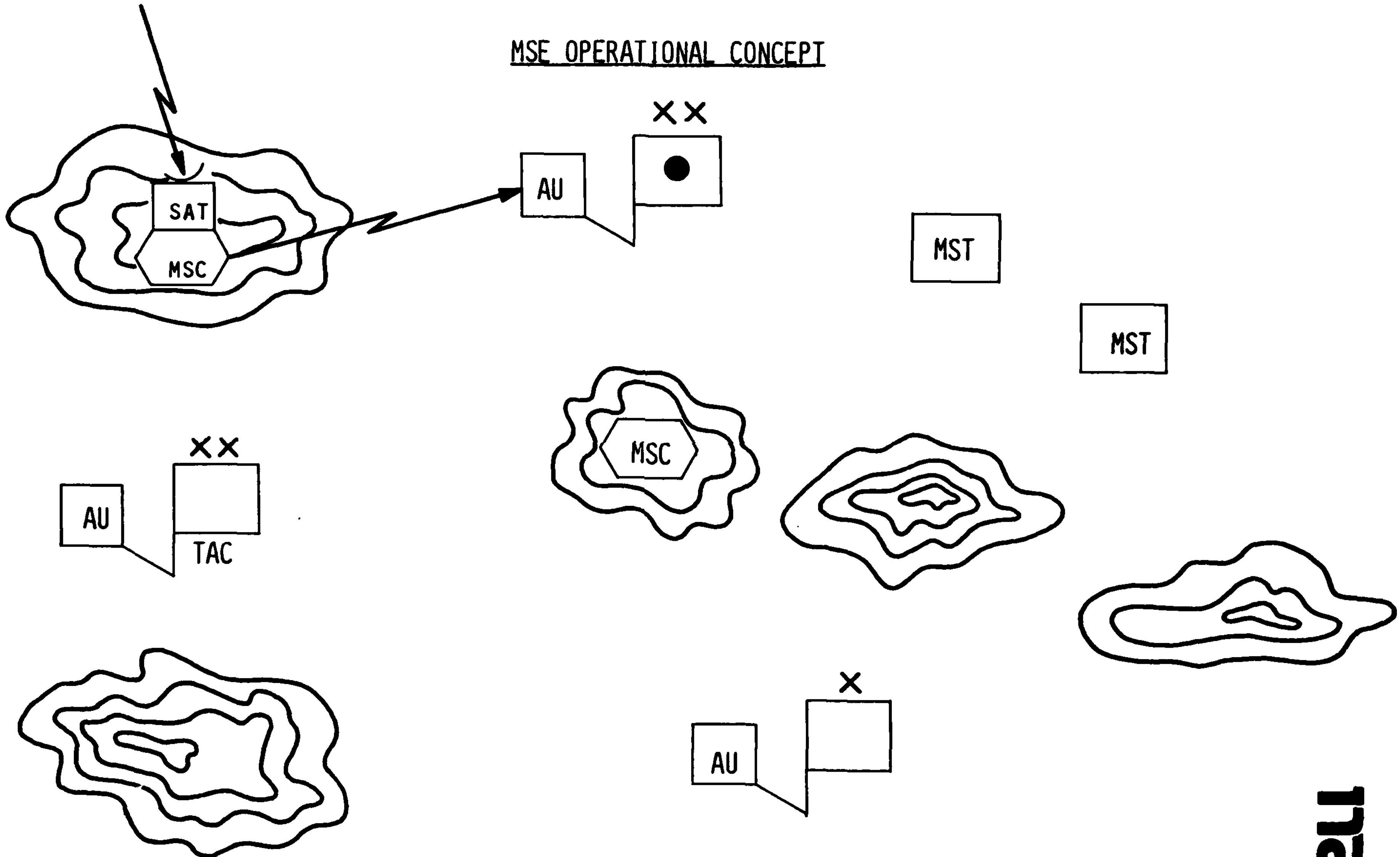


MSE OPERATIONAL CONCEPT



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TYPES OF REQUIREMENTS
(WITHIN DIVISION)

GROUP ID	SWITCHING TIME (SECONDS)	DATA RATE (KBPS)	CONTINUITY (CONTINUOUS(C) OR INTERMITTANT(I))	COMMENT
A	0 + (R. T.)	1.2	C	PR-? MSE-NO
A	0 + (R.T.)	1.2	I	PR-?,MSE-NO
C	0 + (R.T.)	16.0	C	DEDICATED LINKS
C	0 + (R.T.)	16.0	I	PR-?,MSE-NO
D	0 + (R.T.)	41^{+} - 1K	C,I	DEDICATED LINKS
E	1	1.2	I	PR,MSE-YES
-(F)*	2 - 5	2.4	?	DIV - CORP
BATCH	SCHEDULED	1.2 - 2.4	I	MSE,PR-YES
I	15^{+}	1.2	I	MSE,PR-YES
I	15^{+}	32	I	PR,MSE-YES
-(G)*	7 - 15	1.2 - 32	I	PR, MSE-YES

*F, G IDENTIFICATION ASSIGNED BY NAC
R.T. - REAL TIME

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SUMMARY
MSE, PACKET RADIO RESOURCES
INTRA-DIVISION DATA REQUIREMENTS

GROUP	MSE CHANNELS/BUSY HR	PACKET RADIO KBPS(BUSY HR)	COMMENT
A,CON.	-	-	DEDICATED LINKS
A,INT	9	.3	SWITCHING/QUEUEING = .06
C,INT	20	10.8	FEASIBILITY QUESTIONABLE
C,CONT	-	-	DEDICATED LINKS
GROUP D	-	-	DEDICATED LINKS
-(F)	-	-	NO REQUIREMENTS
GROUP E	48	39.5	
BATCH	8	18.6	UNIFORMLY SCHEDULED OVER 16 HOUR DAY
I	.7	.2	
-(G)	1.8	1.3	
TOTAL EXCLUDING RT:	58.5	59.8	
TOTAL INCLUDING RT:	87.5	70.7	

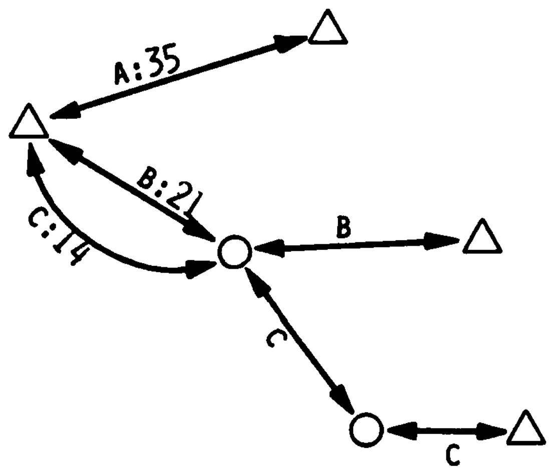
NOTE: REQUIREMENTS DO NOT INCLUDE POSSIBLE TAIL CIRCUITS TERMINATING WITHIN DIVISION; NEED LINES WITH UNKNOWN VOLUMES WERE OMITTED.

VOICE REQUIREMENTS*

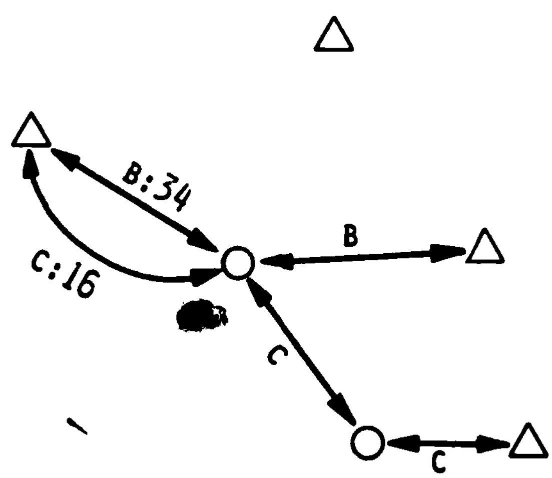
TYPE OF CONNECTION	CALLS IN PROGRESS	
	NORMAL MODE	ECCMMODE
DIRECT (ONE HOP)	35	-
ONE INTERMEDIATE RELAY (TWO HOP)	21	34
TWO INTERMEDIATE RELAYS (THREE HOP)	14	16
TOTAL CALLS	70	50
TOTAL EFFECTIVE CHANNELS USED	119	116

*(SOURCE: "PERFORMANCE SPECIFICATION FOR THE MOBILE SUBSCRIBER CENTRAL", TT-BI-9201-0063, 30 APRIL 1978, DRAFT, JOINT TACTICAL COMM. OFFICE)

MSE VOICE CALLS



NORMAL MODE



ECCM MODE

△ TERMINAL

○ RELAY

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MSE SUBSYSTEM SPECIFICATIONS

- MAXIMUM CONFIGURATION

  9 MSC'S

  400 MST'S

  60 2-CHANNEL AU'S

  20 4-CHANNEL AU'S

- COVERAGE: 25 X 30 KM FOR DIVISION
- MSC CAPACITY: UP TO 12 SIMULTANEOUS CALLS
- SUBSYSTEM CAPACITY: UP TO 70 SIMULTANEOUS CALLS

PACKET RADIO, MSE CORRESPONDENCES

• PACKET RADIO TERMINAL (PRT):	MST
• PACKET RADIO STATION:	MSC
• PACKET RADIO TERMINALS + : CONTROL UNIT + STATIC SUBSYSTEM TERMINATION UNIT = (PRAU)	AU

IN ANALYSIS PERFORMED, USE DIRECT ONE-TO-ONE REPLACEMENT

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MSE REQUIREMENTS
(BUSY HOUR)

COVERAGE: 25 X 30KM, ASSUME ALL POINTS CAN INTERFERE
(NO SPACE DIVERSITY)

DATA BITS PER CHANNEL: 16KBPS

BANDWIDTH PER CHANNEL: 25KHz

TOTAL ONE HOP DATA: 99 CHANNELS
(EXCLUDING R.T. REQUIREMENTS)

TOTAL ONE HOP VOICE: 119 CHANNELS

TOTAL NUMBER OF CHANNELS REQUIRED: 218

SYSTEM BANDWIDTH FOR DATA: 2.48MHz

SYSTEM BANDWIDTH FOR VOICE: 2.98MHz

TOTAL SYSTEM BANDWIDTH REQUIRED: 5.46MHz

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APPROACH TO MIXED VOICE/DATA REQUIREMENTS

- COMBINE MSE AND PACKET RADIO APPROACHES
  - MULTIPLE CHANNELS (FREQUENCIES OR CODES)
  - BROADCAST USE OF CHANNELS
  - SLOTTED ALOHA ON CHANNELS (30% EFFICIENCY)
  - ASSUME SAME EFFICIENCY (BITS/HERTZ) FOR MSE AND PACKET RADIO

SUMMARY REQUIREMENTS
PLUS OVERHEADS
PACKET RADIO FOR DATA REQUIREMENTS
(INTRA DIVISION, NON REAL TIME)

- TOTAL INFORMATION TRAFFIC PER BUSY HOUR: 59.8KBPS
- AREA COVERAGE: 25 X 30 KM
- OVERHEAD: 20% $\Longrightarrow$ TOTAL TRAFFIC $\approx$ 71.8KBPS
- EFFECTIVE NET DATA TRAFFIC (FOLLOWING VOICE PATTERNS)

  = 122KBPS

PACKET RADIO FOR VOICE REQUIREMENTS
(2.4KBPS VOICE RATE)

- MAXIMUM CALLS IN PROGRESS: 70
- TOTAL EFFECTIVE ONE-HOP VOICE CALLS: 119
- VOICE PACKETIZING: 100MS (240 BITS), 96 BIT HEADER
- TOTAL PACKET VOICE LOAD: 400KBPS

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PACKET RADIO FOR VOICE

- VOICE DIGITIZATION RATE
  - A. 2.4KBPS
  - B. 1.2KBPS
- VOICE PACKETIZATION RATE: 100MS
- HEADER OVERHEAD (96 BITS)
  - A. 40%
  - B. 80%
- CHANNEL PROCEDURE: SLOTTED ALOHA

  EFFICIENCY: .3
- CODING EFFICIENCY: MSE (16KBPS PER 25KHz CHANNEL) = .64
- EFFECTIVE ONE HOP VOICE CALLS: 119
- BANDWIDTH REQUIRED FOR PACKET VOICE
  - A. 2.08MHz
  - B. 1.34MHz

(BANDWIDTH FOR MSE VOICE = 2.98MHz)

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SUMMARY

MSE VERSUS COMBINED PACKET RADIO/MSE SYSTEM

BANDWIDTH REQUIRED

REQUIREMENTS	MSE	MSE/PR (2.4KBPS VOICE)	MSE/PR (1.2KBPS VOICE)
BASIC SYSTEM FOR DATA (NO VOICE)	2.49MHz	.64MHz	.64MHz
PLUS APPROPRIATE R.T. REQUIREMENTS*	3.72MHz	.75MHz	.75MHz
BASIC SYSTEM FOR VOICE	2.98MHz	2.08MHz	1.34MHz
COMBINED VOICE AND DATA	6.7MHz	2.83MHz	2.09MHz

*IN MSE, REAL TIME REQUIREMENTS HANDLED AS DEDICATED CHANNELS

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AREAS FOR FURTHER STUDY

- FULLER ANALYSIS OF REQUIREMENTS
- EXACT NATURE OF "REAL TIME" REQUIREMENTS
  - MESSAGE FRAMING, BUFFERING
  - TRUE SPEEDS OF SERVICE REQUIRED
- MULTIPLEXING OF DATA REQUIREMENTS ON MSE
- CHANNEL ACCESS PROTOCOLS FOR PACKET VOICE CAN DO BETTER THAN .3 SLOTTED ALOHA EFFICIENCY USED
- CHANNEL CODING EFFICIENCY (16KBPS/25KHz) USED FOR PACKET RADIO CAN BE IMPROVED FOR WIDER BAND PACKET RADIO CHANNELS
- RANGE/DATA RATE TRADEOFFS TO ACHIEVE SOME SPATIAL DIVERSITY FOR PACKET RADIO AND/OR MSE
- DYNAMIC VERSUS STEADY STATE SYSTEM ANALYSES
- DETAILED HARDWARE IMPACT ANALYSES

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PACKET RADIO DEPLOYMENT STUDY.(U)
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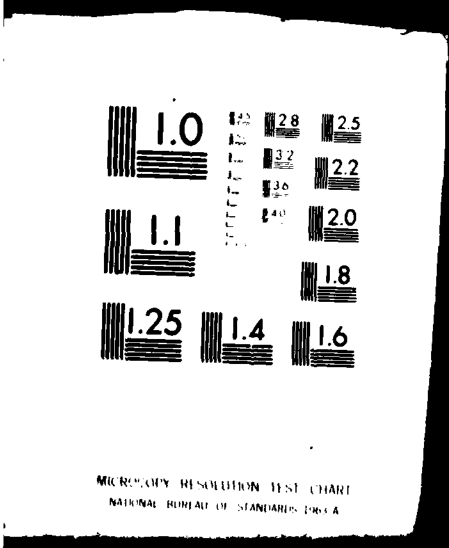

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